REPORT OF
DEPARTMENT OF DEFENSE
ADVISORY GROUP ON ELECTRON DEVICES

SPECIAL TECHNOLOGY AREA REVIEW

ON

RF APPLICATIONS FOR WIDE BANDGAP TECHNOLOGY

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WIDE BANDGAP RF TECHNOLOGY
SPECIAL TECHNOLOGY AREA REVIEW

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EXECUTIVE SUMMARY

The objective of this AGED Working Group A Special Technology Area Review (STAR) was to examine the status of wide bandgap technology development and identify opportunities for applying this technology to DoD systems that operate at RF, microwave or millimeter-wave frequencies. The information exchanged at the STAR is expected to be of use to the Services and DoD agencies during their formulation of an investment strategy for realizing the potential benefits to the DoD of wide-bandgap materials, devices and associated technologies.

Wide bandgap materials are semiconductors which have an intrinsic energy gap of 2 eV or greater. There are a number of these materials but the two most common are Silicon Carbide (SiC) and Gallium Nitride (GaN). As a result, the STAR focused almost exclusively upon them. These materials have the highly desirable characteristics of being able to operate at very high power densities, high voltage, and at high temperatures. Furthermore, they exhibit very high electronic carrier velocities and have a high level of thermal conductance. These semiconductors also have the ability to emit and detect radiation in the blue and UV portion of the optical spectrum which makes them of great interest to laser and LED manufacturers. During the past few years, a number of promising microwave performance results have been achieved for SiC and GaN devices. Representative state-of-the-art results include the achievement of 80 watts of CW power at S-band from a SiC MESFET, and 40 watts of pulsed power at X-band from a GaN hybrid transistor. Most recently, high power GaN MMICs have also been demonstrated. Desirable material properties coupled with encouraging microwave performance results have stimulated strong interest in assessing the promise of this technology area for advancing DoD system capabilities and improving system reliability.

The STAR was convened at the Naval Research Laboratory, Washington, DC, on April 26 and 27, 2000. A distinguished group of speakers from universities, wide bandgap material and device suppliers, military system development companies, a market projection firm, and the Government presented information about wide bandgap material and device physical properties, current device and integrated circuit performance and problems, on-going DoD and industry supported technology development programs and promising areas for technology application. The speakers interacted extensively with the AGED Working Group A membership and other attendees at the STAR, answering questions and discussing important issues.

The following key findings and recommendations emerged from speakers' presentations and subsequent discussions with the AGED Working Group A membership. A complete list of findings and recommendations is also provided, beginning on page 51 of this report.

KEY FINDINGS

This technology has highly desirable characteristics; encouraging microwave frequency performance results have been achieved.

1. Wide bandgap (WBG) RF technology based on SiC and/or GaN offers a potential 10-fold increase in power at a given frequency over current GaAs technology. Small periphery GaN HEMTs have demonstrated a power density of 9.8 W/mm at X-band, seven times that of the best GaAs HEMTs. Large periphery (8 mm) AlGaN HEMTs have been demonstrated with 50 W (pulsed) of

total output power at a power density of 6.5 W/mm, which is 10 times the power density in large periphery GaAs transistors.

2. The high operating voltage of WBG RF technology offers a potential efficiency advantage at the device level, circuit level (more efficient combining as a result of higher transistor impedance), and subsystem level (the higher local bus voltage enables more efficient prime power distribution and conversion).

3. At frequencies below 30 GHz, WBG RF technology offers a significant (~10x) power-bandwidth product advantage over other solid state technologies as a result of higher power density, high operating voltage, and high impedance.

4. Excellent proof-of-principle SiC and GaN microwave devices have been reported.

However, substantial additional development and technology maturation tasks must be carried out to accurately assess and subsequently realize the potential of wide bandgap devices and integrated circuits for meeting DoD system needs. Some key challenges that must be met include the following:

5. The size, quality, and availability of semi-insulating 4H SiC substrates are presently insufficient to support large DoD system programs.

6. WBG epitaxy needs further improvement and fundamental understanding of background doping, large area uniformity, and reproducibility.

7. Microwave trapping effects are evident in WBG RF devices. These traps have been significantly reduced in the best devices, but this area requires more investigation.

8. Limited reliability data exists for SiC microwave devices, and none exists for GaN transistors.

9. Reproducibility and yield analyses have not been determined.

10. Present packaging technology needs to be improved to support the high power density and high operating voltage of some WBG microwave components. Packaging and thermal management may be the performance limiter for WBG microwave power devices and amplifiers.

11. If perceived wide bandgap technology benefits can be realized, DoD systems with superior capabilities and operating characteristics will result.

12. If the projected linearity and dynamic range of WBG microwave technology can be realized it should enable simultaneous multifunction electromagnetic systems.

13. WBG RF technology may be an enabling technology for versatile, decoys and UAVs.

14. WBG RF technology, when mature, could enhance the performance of Active Electronically Scanned Arrays (AESAs), especially when aperture size is limited, by providing

higher power per element compared to alternative solid state technologies. AESA radars are being developed because of their ability to rapidly steer the beam electronically. WBG RF technology is being considered for use in Navy Theater Wide (NTW) Ship Self Defense and Theater Ballistic Missile Defense (TBMD) radars.

15. Based on demonstrated transistor noise performance, AlGaN HEMTs could potentially allow robust, high dynamic range, receivers with a simplified receiver design and a reduced overall receiver noise figure compared to present approaches. This is an active area of research.

PRINCIPAL RECOMMENDATION

The principal recommendation of this STAR is that, in order to realize the promise offered by wide bandgap technology for increasing the capabilities of DoD systems, a comprehensive technology development and maturation program must be undertaken. The estimated investment to make available appropriate material, devices, circuits and packages totals approximately $50M/year. This DoD-wide effort should be programmed no later than POM FY03. The total estimated new funding required is $150-200M over 5 years. This will allow DoD system insertion opportunities in the FY 06 to FY 07 time period to be addressed.

Additional key recommendations are as follows:

1. Appropriate semi-insulating substrate materials, of sufficient size and with suitable characteristics, including cost, must be developed and be readily available.

2. Epitaxial growth capabilities must be developed that are capable of producing material with characteristics leading to high performance microwave devices and MMICs. This material must be reproducible and available in sufficient quantities to meet DoD needs from both quantity and cost perspectives.

3. A comprehensive WBG RF device and circuit technology maturation program must be undertaken to bring WBG RF technology to a level of maturity commensurate with EMD transition.

4. The WBG RF technology program must be directly coupled to the substrate and epitaxy tasks noted in 1 and 2 above. The program must include quantitative device modeling, epitaxy, processing, testing, CAD, packaging, thermal management, failure analysis, reliability, cost models, statistical process control, and yield analysis.

5. A detailed technology roadmap must be developed to ensure that transition opportunities are realized. A system impact study must be performed, or assembled from existing reports, to establish specific device and amplifier goals for the program consistent with system insertion targets. A business plan should be developed to enhance the likelihood of establishing and maintaining a continuing, cost-effective source of WBG RF technology for use in DoD systems.

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TERMS OF REFERENCE

PRIMARY OBJECTIVE

The objective of this STAR is to provide information to aid DoD agencies in planning future investments in the development of wide-bandgap materials, devices, and associated technologies for RF applications.

SUPPORTING OBJECTIVES

1. Evaluate the present status and progress of the last five years in wide-bandgap technology that is applicable to DoD RF applications.

2. Elucidate the technical barriers that are addressed by wide-bandgap technology as applied to DoD's unique RF requirements.

3. Identify and prioritize the current impediments of wide-bandgap technology to address the technical barriers in terms of technical performance, availability, and affordability.

4. Assess the current investments in wide-bandgap technology in terms of supporting future DoD systems.

5. Propose an investment strategy and an overarching roadmap for RF-related wide-bandgap technology for DoD to ensure meeting future system requirements and to maximize return on investment.

DEFINITIONS

Materials: Wide-bandgap materials are those semiconductor materials that exhibit a bandgap of at least 2 eV and whose conductivity can be modulated by controlled doping with impurities and variable alloy compositions. For purposes of this STAR, the primary materials to be considered are SiC and GaN with associated ternary compounds. However, recent advances in alternative wide-bandgap materials, such as ZnO, will be briefly noted.

Technologies: Wide-bandgap technology for RF applications includes: bulk material, epitaxy and substrates; device and circuit processing of hybrid and MMIC implementations; unique device modeling and circuit design issues associated with wide-bandgap materials; unique packaging configurations; and test capabilities required to assess unique characteristics of wide-bandgap devices and circuits.

Applications: For the purposes of this STAR, RF applications of wide-bandgap technology address those devices and circuits that yield useful functions at frequencies primarily between 0.1 GHz and 100 GHz. Examples of these devices are field effect and bipolar transistors, mixer/detector diodes, IMPATT (IMPact avalanche transit time) diodes, cold-cathodes, and other novel devices enabled by unique characteristics of the wide-bandgap materials. Example circuits cover both linear and nonlinear functions, and include amplifiers, mixers, oscillators, and switches. The RF systems and subsystems addressed by wide-bandgap technology include surface, air and space based sensors for communications, radar, intelligence, surveillance, reconnaissance (ISR), electronic warfare (EW), and electronic countermeasures (ECM and ECCM).

Barriers: Technical barriers are conflicts between fundamental physical and engineering constraints and the needed functionality required to enable a device, circuit, or system in a DoD mission. An example of a technical barrier is the conflict between the need for ultra-wide bandwidth of some ISR and EW missions, and the limits on prime power, volume and environmental control. This barrier results in the impetus for compact, high efficiency components.

Impediments: A technical impediment is that fundamental physical or engineering problem that must be solved to overcome an identified technical barrier. For example, an impediment to realizing a robust, high-efficiency device may be the presence of too many material-based defects, leakage, or lossy electrical contacts. To remove the impediment will require the further advancement of wide-bandgap material growth and device processing.

QUESTIONS TO BE ADDRESSED

1. What are the RF applications and systems that will particularly benefit from wide-bandgap technology? What are the status and prospects of early insertion efforts, i.e. TPS-75, Firefinder? What difference will it make if technology efforts are successful?

2. What are the RF technical barriers best addressed by wide-bandgap technology? What are the impediments? Can the barriers and impediments4 be prioritized with respect to return on investment?

3. What is the proper mix of 6.1, 6.2, and 6.3 funds? Has the technology advanced beyond 6.1? What is the proper mix of materials and device investments? Are appropriate substrates available? Has the technology progressed such that materials can support device and circuit development? What are the potential benefits of a DoD organized material/device correlation program? Are there potential impediments at the circuit, package and subsystem levels?

4. What aspects of wide-bandgap technology are providing technology push and what aspects are the results of application pull? What issues can be addressed with the proper leveraging of commercial investments? If commercial investments in wide-bandgap technology are dominated by LED and other electro-optical applications, which of their technical impediments are shared with RF applications, and which are likely to be solved with the commercial investments?

5. What is the proper mix of flip-chip, hybrid, and MMIC technology that is appropriate for the current state of material availability and cost? Which support technologies, such as device modeling or high power/temperature packaging require support?

6. Is the technology at a state where production RF devices and circuits can be expected to deliver the necessary performance for existing DoD systems or next-generation systems? Is there an infrastructure to support pilot production? What is the current availability and cost of wide-

bandgap components and what will be minimally required to enable insertion for either DoD or commercial applications? What are the cost drivers?

7. What are the current investments and to what degree do the investments complement goals and objectives of the various investors? Is there an organized or overarching view of DoD's wide-bandgap technology development programs, and to what extent should that role be centralized?

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AGENDA

Wednesday, 26 April 2000

Overview

8:00-8:10am	Introduction	M. Calcatera (AFRL)
8:10-8:30am	Wide Bandgap Technology Overview	B. Trew (OSD)
8:30-8:50am	Wide Bandgap for RF	J. Palmour (Cree)
8:50-9:00am	Wide Bandgap Market Projections	H. Rodeen (Strategies Unlimited)

University Presentations

9:00-9:30am	Wide Bandgap Physical Properties, Potentials, Device Types	P. Asbeck (UCSD)
9:30-10:00am	HFETs, HBTs	U. Mishra (UCSB)
10:00-10:30am	Wide Bandgap Technology	L. Eastman (Cornell)

Break 10:30-10:45am

Government Presentations

10:45-11:15am	DARPA Perspective and Programs	E. Martinez (DARPA)
11:15-11:45am	ONR Programs and Off-shore Developments	J. Zolper (ONR)
11:45-12:15pm	Wide Bandgap Devices & Circuits for Electronic Attack Systems	J. Lawrence (NRL)
12:15-12:45pm	New E/M Concepts Enabled by Wide Bandgap Device and Circuit Technology	M. Yoder (ONR)

Lunch 12:45-1:15pm

Government Presentations, continued

1:15-1:45pm	Mid-Term Multifunctional Electromagnetic Systems Demonstration	G. Tavik (NRL)
1:45-2:15pm	DoD Materials Roadmap, Epitaxy Materials Issues	B. Shanabrook (NRL)
2:15-2:45pm	Title III Programs, Bulk Materials Issues	L. Rea (AFRL)

Break 2:45-3:00pm

Government Presentations, continued

3:00-3:30pm	Air Force Applications, Technology Programs	T. Jenkins (AFRL)
3:30-4:30pm	Army Applications, Technology Programs	J. McGarrity (ARL)
4:30-5:00pm	Ballistic Missile Defense Organization Applications	B. Kopp (Johns Hopkins)

Adjourn

AGENDA (continued)

Thursday, 27 April 2000

Industry Presentations (Government-only)

Technology

8:00-8:30am	Materials, HFETs, MESFETs	J. Palmour (Cree)
8:30-9:00am	Device Technology, Packaging	M. Adlerstein (Raytheon)
9:00-9:30am	HFETs	P. Parikh (Nitres)
9:30-10:00am	GaN Devices	D. Reep (Lockheed Martin)
10:00-10:30am	GaN and AlGaN MODFETs	B. Stanchina (HRL)
10:30-11:00am	Wide Bandgap Technology	R. Chris Clarke (Northrop Grumman)

Break 11:00-11:15am

Applications

11:15-12:15am	MESFET and SITs for TPS-75 Radar	A. Morse, M. Fitelson (Northrop Grumman)
12:15-12:45pm	System Needs and Insertions	D. Laighton (Raytheon)
12:45-1:15pm	Wide Bandgap Technology Applications	E. Johnson (Lockheed Martin)

Lunch 1:15-2:00pm

Wrap-Up Session (Government-only) 2:00pm onward

Adjourn

PRESENTATION SUMMARIES

SUMMARY OF OVERVIEW PRESENTATIONS

Dr. Robert (Bob) J. Trew, Director of Basic Research ODUSD (S&T) U.S. Department of Defense

Dr. Trew summarized the prior DoD S&T investment in wide bandgap technology research and development. He noted that ONR has been a principal sponsor of Wide Bandgap (WBG) technology development. The MURI (Multidisciplinary-research University Research Initiative) (6.1) programs have also invested significant funding in WBG device development; program support by MURI has led to many of the current advances. Five universities have played major roles in the MURI Wide Bandgap program: Purdue, Cornell, UCSB, NCSU and UCSD. Their work has included research on manufacturable power switching devices, broadband amplifiers, compact power sources, heterojunction power switching, radiation-hard physics and interface electronics. Dr Trew anticipates that there will be a new MURI effort beginning in FY 01.

He next addressed specific issues that impact current device performance. One of these is that the negative differential mobility of GaN, predicted by theory, hasn't been verified by experiment. As a result, it is difficult to produce WBG Gunn devices or other device types that are dependent upon this phenomenon. P-type doping in wide bandgap materials, particularly in GaN and AlGaN, results in low mobility characteristics. Dr. Trew believes that this phenomenon precludes wide bandgap microwave HBTs (heterojunction bipolar transistor) with acceptable performance characteristics. He recommends that future efforts focus upon development of HEMTs, MESFETs and SITs (static induction transistor), all of which make use of n-type active regions.

Dr. Trew continued by comparing some of the issues addressed previously for GaAs technology to similar challenges impacting current wide bandgap material characteristics and performance. He showed pulsed I-V curves for a GaAs MESFET operating at various levels of drain and gate bias and discussed how analysis of these curves indicated the presence of pronounced trapping effects. Maximum power added efficiency can be predicted from analysis of the dynamic load line of a given device. Dr. Trew also stated that the calculated maximum power density of 4H-SiC MESFET amplifiers is 5-6 watts/mm. In his opinion, the most important figure of merit for WBG MESFETs is f_t not f_{max}. He predicted that acceptable performance for 4H-SiC MESFETs would be achieved at frequencies through X-band; possibly at frequencies as high as Ku-band

Dr. Trew concluded his presentation with results from measurements of a commercially available Toshiba **GaAs** FET (field effect transistor) amplifier, operating Class A. Its: power output was almost 20 watts with an associated PAE (power-added efficiency) of 26% and gain of 6-7 dB at 10 GHz. He noted that "this is the competition".

Dr. Trew summarized his presentation as follows:

1. 4H-SiC and AlGaN/GaN FETs offer significant improvements in RF output power (up to an order of magnitude for AlGaN/GaN HFETs [Heterostructure Field Effect Transistor])

2. Material quality, particularly substrates for GaN, is still a problem (defects, traps)
3. Approaches for handling thermal dissipation need to be improved
4. Trapping effects (surface, bulk, and interface) need to be addressed
5. Use of P-type material presents a major problem - HBT 's with acceptable performance will be extremely difficult to realize (Quotable quote: "Transport is so bad, why screw around with this.")

Dr. John W. Palmour, Director Advanced Devices, Cree, Inc.

Dr. Palmour started his presentation with a description of Cree, Inc., widely recognized as the premier SiC materials company in the world and also as a leader in the production of SiC and GaN devices. Cree 's financial status was stated as follows: Revenue (not just for RF devices)--FY 99: $60,050,000; FY 00 (nine months) $72,342,000. The revenue breakdown for the first six months of 2000 was: 57% from LED sales; 35% from material sales (including gemstones) (actually about 17-20% of revenue from material sales other than gemstones); 8% from contracts. Cree, Inc. was noted as being listed as the 15th fastest growing company in Fortune magazine. At the time of the presentation, Cree had 640 employees. Thirty more were expected to be added as a result of the acquisition of Nitres (scheduled to officially occur on April 28, 2000). Currently Cree has a 250,000 square feet facility. An additional 350,000 square feet of space is under construction (and scheduled for completion in November 2000). A secondary stock offering, held during January 2000, raised $266 million in capital.

Dr. Palmour succinctly explained Cree's rational for concentrating on expanding LED production capabilities, " Cree is an Optoelectronics Company; LED research has an immediate payback; laser announcements [directly] impact our stock price."

Dr. Palmour next discussed Cree's wide bandgap RF technology activities. To expand *commercial* microwave business it recently hired Ray Pengelly to be General Manager of its COMMERCIAL RF business. Cree is funding its commercial microwave development under IR&D at $3M/year and has also invested $3.5M in capital equipment for microwave device production. Dr. Palmour projected that commercial RF applications would soon constitute the single largest microwave program at Cree. Efforts on this program will be focused upon relatively low power parts that operate between 1 and 6 GHz. The principal competitor for these parts is Si LDMOS (lateral double-diffused metal-oxide semiconductor). He noted that, at present, there is not a large commercial demand for microwave GaN devices and *no* commercial demand for wide bandgap pulsed power MMICs, since the needs of most commercial applications can be met with hybrid solutions.

Dr. Palmour next described the status of Cree's SiC wafers. Cree is currently producing device quality 2" wafers and has fabricated MMICs using both SiC MESFETs and GaN HEMTs. He noted that very few of these MMICs can be included on a 2" wafer (large chip size).

In October 1999, Cree also released 3" diameter 6H-SiC n-type substrates for sale. Their intended application is for use in conjunction with GaN opto applications and their current price is $1980/wafer. This is slightly lower in $/cm^2 than the cost of the 2" diameter product. Currently 4H-SiC and SiC epi are not yet available commercially. Other Cree CY 2000 wafer prices that he presented include: $10/cm^2 for 2" SiC (presumably N-type 4H or 6H); $125/cm^2 for 4H semi-insulating substrates. Finally, Dr. Palmour noted that 4" SiC R&D wafers were prototyped during 1999 but no semi-insulating 4" SiC wafers have yet been produced.

Next, commercial opportunities for wide bandgap RF technology were discussed. Dr. Palmour noted that the first Cree SiC RF product was introduced in June 1999. This was a 10 W SiC MESFET, which operates at 2-3 GHz. Key business targets are the 2-6 GHz wireless market. --3G (third generation), WLL (wireless local loop), MMDS (Multi-Point Microwave Distribution System), commercial mobile communications, wireless Internet and radars for air traffic control.

Cree plans a RF product family including:

A driver chip operating, at 48 volts, in frequency bands from 400 MHz up to 3.7 GHz.

High Linearity Class A Drivers	High Power Class AB Output
* 10 watts	10 watts
60 watts	60 watts
	120 watts

* = Initial product release, June 1999

Compared with Si LDMOS amplifiers, SiC amplifiers offer twice the linear power and 40% higher efficiency (14% vs. 10% at adjacent channel power rejection level of operation)

Note: In response to a question from the Eliot Cohen as to how GaAs performance would compare, Dr. Palmour commented, "we need to measure that".

Dr. Palmour claimed the following advantages of Wide Bandgap Devices for DoD Radar Applications:

IF wide bandgap devices can be produced with 5x the RF output power of competing devices (e.g., GaAs):

THEN:

- Target detection range will be increased by 40%
- Greater TBM Discrimination will be possible

GaN vs. SiC Commentary:

- HEMT offers undeniable advantages of better f_t and gain--particularly important for operation at X-band and higher frequencies
- SiC devices with huge gate peripheries (48 mm) have been fabricated with very good performance at lower frequencies (Question: what was the yield?)
- GaN and SiC are roughly equal (in performance) at S-band; cross-over point currently at 8 GHz

Problems facing WBG Microwave Devices:

- Trapping effects--requires material/process research
- Packaging--High power densities worthless without high power dissipation packages
- Reliability: Little data for SiC; virtually no data for GaN

- Cost: Wafer diameters must be increased along with device yield; epitaxial uniformity currently constitutes the single biggest yield hit

Key quotes from Dr Palmour:
"...Left on its own, Cree would slowly develop low power CW discrete parts of little DoD benefit"
"There are many critical issues yet to be solved to make these technologies (SiC and GaN) really viable"
Commercial market: 1-6 GHz

Mr. Hank Rodeen, Strategies Unlimited

Hank Rodeen represented Strategies Unlimited, which does market studies of various technologies. Its staff has recent completed a new study of wide bandgap technology, focused on GaN-based components.

Rodeen presented the following information to the STAR:

- Before bright blue LEDs were developed (1993), total sales of blue, white and green LEDs were < $5M
- In 1999, total sales of blue, white and green LEDs exceeded $400M
- By 2009, total market sales of all GaN based products are expected to be approximately $5 billion. Of this amount, $4.3 billion will be for opto-electronic devices and $400-500 million for all GaN-based electronic[1] devices

	2000	2003	2006	2009	CAGR
LEDs	$572M	$983M	$1627M	$2344M	19%
Laser Diodes (Blue and for Optical Storage)	<$10M	$27M	$923M	$2070M	106%

Sales Ranking (2009):

- HDDVD-ROM: $960M
- Recordable DVD Video: $450M
- Video Games: $330M
- HDDVD-RAM $270M
- Other DVD $ 60M

GaN Electron Device Sales Forecast:

- 2000: $0
- 2002: $4M

[1] Primarily microwave and millimeter wave devices, switches and solar-blind detectors.

- 2006: $128M
- 2009: $436M

(Note: Previous Strategies Unlimited forecast (prepared in 1997) predicted $12M in sales in 2002 and $90 M in sales during 2006.)

<u>GaN Forecasted Electron Device Sales by Device Type</u>

- Total for 2005: $71 Million
  - RF/Microwave: 74%
  - Power Switches: 6%
  - Power Rectifiers: 5%
  - High Voltage Rectifiers: 5%
  - High Temperature Devices: 10%

- Total for 2009: $436M
  - RF/Microwave: 46%
  - Power Switches: 28%
  - Power Rectifiers: 12%

<u>GaN Forecasted Sales By Market Type</u>

- Total for 2005: $71M
  - Communications: 72%
  - Industrial: 17%
  - Military/Aerospace: 5%
  - Automotive: 3%
  - Aircraft: 3%

- Total for 2009: $436M
  - Communications: 42%
  - Industrial: 33%
  - Military/Aerospace: 12%
  - Automotive (Exterior & Interior Lighting): 10%
  - Aircraft: 3%

Current average selling price for a GaN device = $500
Projected average selling price for a GaN device in 2009 = $125

Mr. Rodeen made the case that the most critical drivers for achieving reduced average selling price are volume of manufacture and crystal quality (both bulk and deposited). He commented that high volume device fabrication with relatively low yield (say 40%) would actually result in lower unit device costs than low volume manufacture with yields approaching 100%. One approach to achieving significant chip price reduction would be to use high volume foundries, e.g., TSMC (Taiwan) and UMC (Taiwan) and Chartered Semiconductor (Singapore), which collectively account for roughly 10% of Si chip output in world) to reduce the cost of wide bandgap ICs by cutting overhead cost per die.

In closing, Mr. Rodeen listed the key obstacles to GaN-based technologies impacting the RF marketplace. He stated these as being:

- GaN crystal quality
- GaN epitaxial layer quality
- P-Type doping density
- Contact resistance
- Metallization schemes
- Device isolation
- Overall yield, volume and cost
- Legal restraints (e.g., Nichia's reluctance to license its technology to others)

SUMMARY OF UNIVERSITY PRESENTATIONS

Peter Asbeck, UCSD: Prospects and Problems with Wide Bandgap Materials

This presentation reviewed the advantages of wide bandgap materials for microwave power transistors and summarized performance prospects and implementation challenges for various device types (HFETs, HBTs, HEMTs).

The breakdown field of GaN reaches 8x that of GaAs, while for 4H-SiC it is about 5x as high as for GaAs. The thermal conductivity of GaN is 3x as high as that of GaAs, and 10x higher for 4H-SiC. The electron velocity at high fields (e.g., at 300 KV/cm) is 2x as large for GaN and SiC as for GaAs. This combination of advantages is extraordinary. It indicates that the power density, as limited by electrical effects, could be 70X higher for GaN than for GaAs. Thermal limits will restrict the upper bound of power dissipation however, limiting it to about 30W/mm assuming a SiC substrate of 100μm thickness (upon which either SiC or GaN active device layers are fabricated. This is 30x higher than that of GaAs. The power obtainable from a single packaged transistor (assumed to be limited by the impedance that can be effectively matched to 50 ohms) is 30x to 50x higher for GaN than for GaAs. The maximum voltage x f_t product is 10x higher for GaN than GaAs.

Wide bandgap materials have lower electron mobility at low fields than GaAs and InGaAs which presents challenges to maintaining high efficiency. It is critical to minimize gate length, to minimize source-gate separation, and to operate with the full voltage swing available as a result of the high breakdown field. Alternatively, high power density could be traded off in favor of efficiency.

Substantial transient velocity overshoot effects in nitrides is also a possibility. This prospect is, so far, relatively unexplored and poorly understood.

Problems in producing wide bandgap devices emerge because of the absence of large, uniform substrates. For the nitrides, all substrates have dislocation densities above $10^8 cm^{-2}$, except those produced using epitaxial lateral overgrowth and pendeoepitaxy techniques. Crystalline defects, impurities, traps and surface states all conspire to produce transient current anomalies in nitride power FETs; these limit the output power and linearity of present devices. Polarization and piezoelectric effects dominate charge densities; these effects may present opportunities for new device designs – many of which remain to be studied.

Vertical devices (as opposed to lateral FETs) offer prospects for designs which have improved breakdown characteristics, are minimally impacted by surface trapping effects, have reduced 1/f noise and potentially better linearity. The HBT is the prototype vertical device, but its performance is challenged by low hole mobility and deep acceptor depth. Other vertical device structure possibilities include the SIT and the hot electron transistor (HET); both of these are majority carrier devices that have potential for high performance. However, both are challenging to implement.

Universities are exploring diverse possibilities that exist, particularly for nitrides, in a very active and wide-ranging research program funded by the DoD. This investment is successfully addressing many of the key underlying physics and chemistry issues.

Umesh Mishra, UCSB: GaN Transistors for Microwave Power Amplifiers

Professor Mishra continued the emphasis on the theme that use of GaN technology will improve microwave amplifiers to the point where new systems can be enabled – through achievement of high output power, high efficiency, high linearity and low phase noise. He provided a review of the UCSB programs aimed at developing both HFETs and HBTs using nitrides – programs that are very advanced, and, in a number of cases, define the state-of-the-art.

HFET power density performance is the result of the ability to operate at high voltage and current. To maximize channel current, UCSB has increased the aluminum content of the barrier layer. Professor Mishra discussed the challenges posed by this, primarily in achieving high quality material. Atomic Force Microscope (AFM) images often depict micro-cracks, pits and enhanced roughness that occur as aluminum concentration increases; these defects translate directly into reduced channel mobility as verified by both theory and experiment. A critical limiting factor for HFET performance, at present, is the dispersion between small signal or DC and large signal RF behavior, which can be related to a voltage and history dependent gate length extension. This phenomenon could be the result of surface states or buffer layer traps. To prevent buffer layer trapping effects, there must be fewer than $10^{16}cm^{-3}$ deep traps in this layer; this will require improvements in crystal growth. For example, in experiments conducted under Dr. Mishra's supervision, it was evident that the incorporation of oxygen and carbon increased as aluminum concentration increased. To avoid surface traps, passivation layers must be implemented. There was clear evidence that trapping effects add to thermal effects in limiting output power of present devices.

HBTs merit investigation because they offer bulk-breakdown limited power density, high linearity and low 1/f noise. The HBT experiments at UCSB have led to devices with a dc current gain as high as 6-8. An assortment of issues make their fabrication very challenging. Etch damage of the base compounds the problem of producing adequate contacts and high-conductivity base layers. Increased base sheet conductivity can be managed with the use of thicker bases, provided that a built-in field is used to minimize the base transit time (although this requires p-type AlGaN or InGaN). The deep Mg acceptor level may lead to dispersion effects particularly for the base-collector (BC) capacitance, and may also result in time-dependent Early voltage phenomena. There may be leakage paths through the emitter-base (EB) and BC junctions associated with dislocations (which are vertical). Various techniques presently being explored offer promise for improved performance include regrown emitter structures, HBTs on LEO (lateral epitaxial overgrowth) material, and fabrication of pnp rather than npn structures.

To make these promises a reality, Professor Mishra highlighted the need for a diverse research effort, encompassing development of GaN substrates, improved epitaxy, damage-free processing, stable passivation and shallow p-type dopants.

Lester Eastman, Cornell University: AlGaN/GaN/SiC HEMT: The Next Generation Microwave Power Amplifier

Professor Eastman reviewed the physics of heterostructure FETs based on AlGaN/GaN layers deposited on SiC substrates. He followed this by a comparison of state-of-the-art values for nitrides and conventional GaAs devices, and offered his view of the future for this technology.

In Cornell HFET designs, channel charges are provided entirely by spontaneous and piezoelectric polarization effects; these allow N_s above 10^{13} cm^{-2} to be easily produced. These high levels can be maintained with good sheet mobility. Experimental values reach 1700 cm^2/Vsec for N_s=1.2e13cm^{-2}, in line with theoretical expectations. With short gates, very high f_t values have been obtained, up to 74GHz with L_g=0.15µm (and an intrinsic f_t of 106 GHz).

To accurately determine power density, thermal limits must be considered in addition to electrical limitations. Simulations were shown of various FET layouts (fishbone, U-shape, T-shape) on both sapphire or SiC substrates of 100µm or 300µm thickness. For thick sapphire, between 2-6 W/mm could be achieved with a 300°C rise between heatsink and channel. However, using a 100µm thick SiC substrate, the computed power density value was extraordinarily high, up to 30 W/mm for a large device.

AlGaN/GaN/SiC HFETs were compared with ones produced from other materials on the basis of the figure-of-merit $P_a f_{10}^2 Z_L$, where P_a is the class A saturated power, f_{10} is the operating frequency at 10dB power gain, and Z_L is the load resistance. For the AlGaN/GaN/SiC FETs a *f.o.m.* of 1.2x10^{23} WHz^2ohm is projected, which is higher by about 50x-100x than the corresponding *f.o.m.* of GaAs p-HEMTs. As a result of this calculation, Professor Eastman predicts that these devices will become the microwave power amplifiers of choice in a large number of DoD and commercial applications[2].

[2] The power/frequency /load electrical figure of merit of AlGaN/GaN HEMT's developed at Cornell University is based on experimental results. By testing HEMT's with gates of different lengths, along the electron flow direction, Dr. Eastman's department obtained the dependence of the cut-off frequency and the drain-source breakdown voltage limit on this length. He used the electrical limit for class A operation, that the maximum power is 1/8 (ΔV ΔI). For ΔV he used the breakdown voltage less a typical knee voltage ≤ 5 V. For ΔI he used the typical 1 A/mm maximum normalized channel current, times the periphery. He then use a load impedance whose value is $\Delta V/\Delta I$. He use an operating frequency that is one fourth of the cut-off frequency, to allow 10 db of power gain at the operating frequency. He used an effective gate length equal to the gate footprint plus twice the barrier thickness, to account for fringing electric fields. With an effective gate length of .20 µm he got 35 V_{ds} breakdown, a value rising linearly with this length. For this same effective gate length he got extrinsic f_t of 74 GHz, a value that was proportional to the reciprocal of this length. Together these resulted in the electrical figure of merit: $P_A f_{10}^2 Z_L = 1.2 \times 10^{23}$ WHz^2-Ω, where P_A is the maximum pulsed microwave power in class A operation, f_{10} is the upper frequency yielding 10 db saturated power gain, and Z_L is the load resistance.

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SUMMARY OF
GOVERNMENT BRIEFINGS

Edgar Martinez, DARPA

Recently completed and ongoing DARPA programs for wide bandgap semiconductors as well as a proposed new effort for GaN based microwave technology development were described. DARPA WBG efforts have been divided into four areas: materials development, power control devices, opto-electronics, and RF solid-state power. The overall program objectives are to advance the state-of-the-art of WBG technology in these four thrust areas.

In the area of materials development, increase of 4H SiC wafer diameter and improved quality have been pursued. Efforts have addressed crystal growth, optimization of wafer and polishing technologies, and epitaxial growth techniques. Programs were sponsored at Cree Research, ATMI, Northrop Grumman, and Litton Airtron. The program at Cree resulted in the demonstration of a 3-inch, n-type 4H SiC wafer with improved wafer surface uniformity and reduced micropipe density, as defined by polarized light imaging.

The program at Northrop Grumman, and subsequent transition of its results to Litton Airtron, focused upon advanced physical vapor transport (APVT) growth of SiC boules. The objective was to use independent control of the Si/C ratio to reduce micropipes and dislocations, increase boule size, increase growth rate, and realize low background doping levels ($< 10^{14}$ cm^{-3}). This effort resulted in the demonstration of two inch 4H-SiC substrates, from inch long boules, using the APVT process

In 1999, under DARPA's Microwave and Analog Front-End Technology (MAFET) program, HRL produced MBE (molecular beam epitaxy) grown AlGaN HEMTs. This program's goal was the demonstration of a 10 W, X-band GaN MODFET with a power density of 10 W/mm. Device fabrication was based upon using MOCVD (metal organic chemical vapor deposition) GaN templates grown on sapphire for use in subsequent MBE growth of layers for the active device. The use of MBE was shown to provide good intra-wafer uniformity (a sigma for I_{dmax} of 4% with MBE versus 28% with MOCVD) over a two-inch wafer. Good DC and small signal MODFET performance was achieved under the program, but the 10 W power output at X-band goal was not.

A DARPA program to develop solar blind UV detectors and focal plane arrays (FPAs) was also discussed. These detectors and detector arrays are intended for use in ground vehicle self-protection and airborne missile threat warning. An AlGaN device can have a cut-off wavelength that makes it insensitive to solar spectrum that would saturate other narrower bandgap solid state detectors, while allowing the simultaneous detection of a missile plume. A primary objective of this program is to realize AlGaN avalanche PIN detectors with an Al-composition ≥ 50%. A core challenge is to achieve high quality AlGaN with such a high Al-composition while also achieving sufficient p-type doping. This program began in FY99. Early efforts are focused on epitaxial growth and techniques to reduce the dislocation density in the GaN and AlGaN films. The program has also supported work at ATMI to demonstrate free-standing GaN substrates, via hybrid vapor phase epitaxy (HVPE) techniques, and laser lift-off from sapphire substrates.

The final section of the briefing focused on a proposed program at DARPA aimed at further development of wide bandgap RF technology. The objectives of this program are a 10 to 100 fold increase in solid state power and multi-octave bandwidth operation. The program plan is to deliver compact, modular, RF power transmitters for sensor and communication applications. The limitation of present solid state technology was demonstrated by showing the nominal current and voltage bias conditions for silicon and GaAs devices as compared with those for GaN. The higher current and voltage capability of GaN transistors is expected to yield a 10 to 100-fold increase in microwave power.

The proposed program has three tasks: 1) to develop electronic grade materials, 2) to demonstrate high power, high efficiency transistors, and 3) to achieve efficient thermal management. The goal of task 1 is low defect density substrates. Work is expected to be focused primarily on producing GaN bulk, or quasi-bulk, substrates. The potential approaches for producing this material include use of HVPE, high pressure/high temperature synthesis, melt solution growth, and solvent assisted growth. Task 2 will include the development and demonstration of both AlGaN HEMTs and HBTs. Task 3 will address packaging of high-power density microwave amplifiers with particular emphasis on addressing thermal management.

The program is expected to push solid state transmitter technology into the power/frequency range where, in the past, only vacuum tubes could provide acceptable performance.

John Zolper, ONR WBG Microwave Programs

Dr. Zolper began with an overview of the critical material properties of WBG materials (SiC and AlGaN) that make them attractive for microwave applications. Table I gives a summary of these properties. First among them is the high critical breakdown field that enables high voltage operation. The second is high electron velocity. The third is high thermal conductivity, particularly that of SiC, on which GaN can be grown. Finally, the AlGaN/GaN system has the major advantage of a heterostructure--enabling a two dimensional electron gas (2DEG) with very high sheet carrier densities of over 1×10^{13} cm^{-2} and a mobility up to 2000 cm^2/Vs.

Table I:
Summary of key materials parameters.

	Si (----)	GaAs (AlGaAs/ InGaAs)	InP (InAlAs/ InGaAs)	4H SiC (-----)	GaN (AlGaN/ GaN)
Bandgap, E_g (eV)	1.1	1.42	1.35	3.26	3.49
Electron mobility, μ (cm^2/Vs)	1500	8500	5400	700	900 (>2000)
Saturated (peak) electron velocity, v_{sat} (v_{peak}) ($x10^7$ cm/s)	1.0 (1.0)	1.0 (2.1)	1.0 (2.3)	2.0 (2.0)	1.5 (2.7)
2DEG sheet electron density, n_s (cm^{-2})	NA	$<4 \times 10^{12}$	$<4x10^{12}$	NA	$1\text{-}2x10^{13}$
Critical breakdown field, E_c (MV/cm)	0.3	0.4	0.5	2.0	3.3
Thermal conductivity, λ (W/cm-K)	1.5	0.5	0.7	4.5 (3.3)[a]	>1.7[b]
Relative dielectric constant (ε_r)	11.8	12.8	12.5	10	9.0

[a] thermal conductivity of SI-SiC
[b] V. M. Asnin, F. H. Pollak, J. Ramer, M. Shurman, and I. Ferguson, Appl. Phys Letts, (submitted May 1999).

Two microwave transistor figures of merit were described: 1) the Johnson figure of merit (JFOM) $\propto(v_{sat}E_c)^2$ and 2) the Baliga high frequency figure of merit (JHFFOM) $\propto (\mu E_c^2)^3$. It was shown that GaN has the highest FOM's with SiC being second. The only material with a higher JFOM and BHFFOM is diamond. However, since diamond can not be controllably doped it is not considered a practical material for microwave applications at this time.

ONR programs for SiC microwave transistor development were reviewed next. Focus has shifted to SiC MESFETs as opposed to prior efforts on SiC SIT. The change resulted from the necessity to achieve wide bandwidth. The sole remaining SiC SIT program, at Northrop Grumman, is focused upon demonstrating an inverted SIT with lower parasitics and, thus, better frequency response. The SiC MESFET programs are leveraging previous ONR core 6.2 work that led to a demonstration of an 80 W CW 4H-SiC MESFET at 3.1 GHz. The new effort, with Cree, has a goal of realizing 175 W CW SiC MESFET MMICs that operate over the 1-5 GHz band. Two of these will be combined off-chip to produce a class B pull/pull amplifier with an anticipated power output of 300 W CW. Its expected efficiency is 30 %.

Dr. Zolper next reviewed the development of AlGaN HEMTs and HBTs. The importance of the large critical breakdown field of GaN, 10 times that of GaAs, was noted to enable higher power

[3] These figures of merit show the relative merits of a given semiconductor for microwave device operation. V_{sat} is the saturated electron velocity, E_c is the critical electric breakdown field, and μ is the carrier (electron) mobility. Values for these parameters for semiconductors of interest are given in Table I.

and high bandwidth amplifiers. The high sheet electron density in AlGaN/GaN heterostructures was explained as being due to the polarization induced field at the interface. This phenomenon includes both spontaneous polarization and piezo-electric polarization; these effects combine to give a sheet electron density proportional to 5×10^{13} cm^{-2} times the Al-mole fraction in the AlGaN barrier layer. This effect enables device structures without extrinsic doping to exhibit sheet electron densities of 1-2×10^{13} cm^{-2}. It was noted, however, that there is evidence of a surface donor at ~1.4 eV induced by the internal fields; the surface must also be properly passivated.

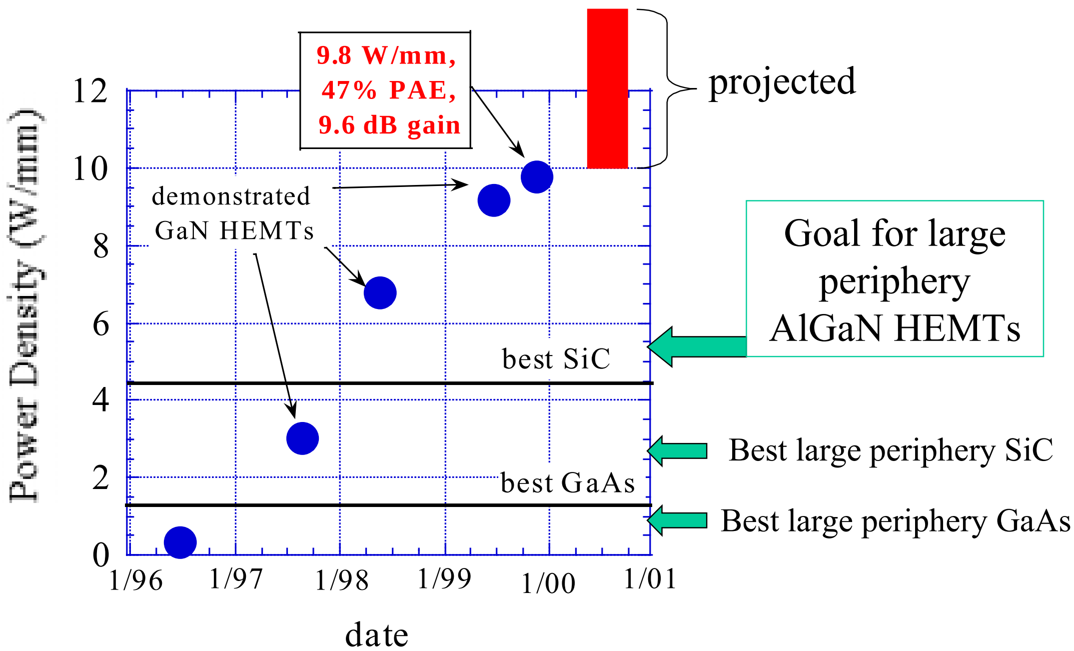

Figure 1: Progress in increasing X-band power density of AlGaN HEMTs.

Progress in device performance was reviewed. AlGaN HEMTs have now demonstrated small signal results equivalent to those of GaAs HEMTs with f_t = 110 GHz and f_{max} = 140 GHz. The improved understanding of device physics and material growth has resulted in steady progress in increasing the microwave power density of small periphery devices. The progress in increasing X-band power density is shown in Figure 1 along with the best results achieved for GaAs HEMTs and SiC MESFETs. The best reported result to-date is a power density of 9.8 W/mm at 8 GHz with an associated gain of 9.6 dB and PAE of 47%. This favorably compares with the best GaAs HEMT result of 1.5 W/mm and the best SiC MESFET result of 4.3 W/mm. It is projected that AlGaN HEMT power density can be increased to 14 W/mm. The present goal for large periphery transistors is also shown. For large periphery AlGaN HEMTs, the goal for power density is 5 W/mm. The best known large GaAs device has a power density of 0.8 W/mm and the best large SiC MESFET has a power density of 2.3 W/mm at X-band.

While power density is always the first metric quoted for a new solid state device technology, achieving high total power from large periphery transistors is a considerably greater challenge. Figure 2 shows the progress that has been made in achieving total power from AlGaN HEMTs.

Recent results have exceeded the "best ever" ones for GaAs HEMTs--16 W from a 25 mm gate periphery, with the demonstration of 51 W (pulsed) at 6 GHz from a transistor only 8 mm wide. This exceeds the power density goal for large periphery devices, mentioned above, by maintaining a power density of 6.5 W/mm in the 8 mm device.

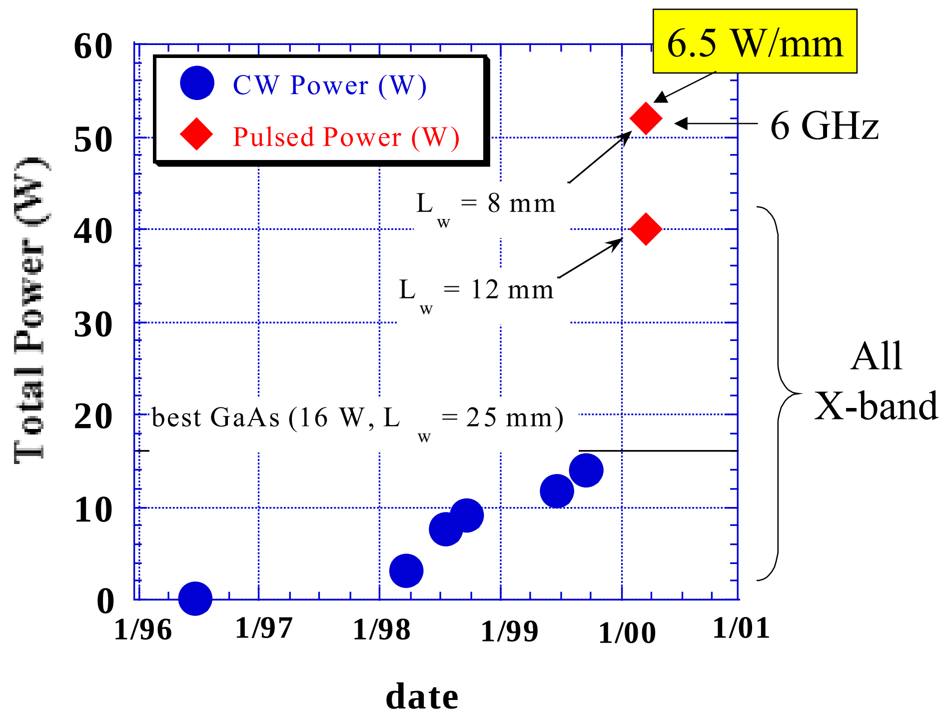

Figure 2: Progress in increasing total microwave power from AlGaN HEMTs.

Dr. Zolper next discussed PAE projections for WBG transistors. It was noted that their high voltage capability, coupled with their high sheet carrier density and their high electron mobility gives rise to an anticipated PAE for AlGaN HEMTs operating Class B that exceeds that of InGaAs channel pHEMTs. Progress to date for AlGaN HEMTs, is compared with that for SiC MESFETs and GaAs HEMTs, in Figure 3. A small periphery AlGaN HEMT has demonstrated a PAE of 62% at X-band.

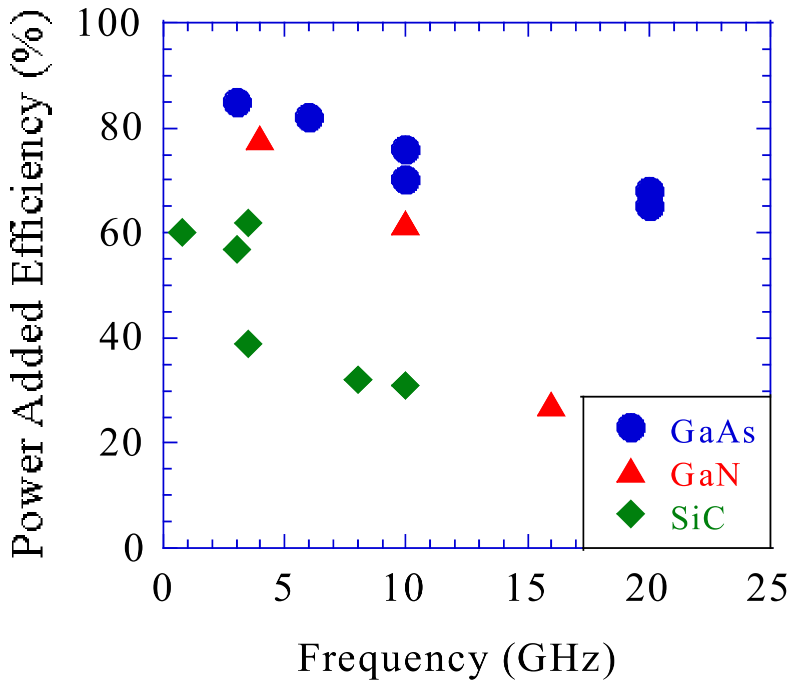

Figure 3: Demonstrated PAE versus frequency for GaAs, GaN, and SiC transistors.

Low noise amplification with AlGaN HEMTs was discussed next. High sheet electron density coupled with a respectable mobility give AlGaN HEMTs a $\mu_e n_s$ product competitive with that of InGaAs pHEMTs. In addition, the large inter-valley separation in the conduction bandgap of GaN (~1.9 eV) reduces inter-valley scattering. The combined effects of these properties result in AlGaN HEMTs having microwave added noise figures that are highly competitive with those of GaAs. For example, a NF of 0.6 dB at 10 GHz was reported. The AlGaN HEMT with the 0.6 dB noise figure also has a breakdown voltage over 60 V. This provides the powerful advantage of enabling a receiver which does not need the protection of a diode limiter (or, at least, will require only a less restrictive limiter). This robust AlGaN LNA (low noise amplifier) without a limiter would have a noise figure below that of the combination of a InGaAs LNA and diode limiter, since the limiter introduces a noise figure component of between 0.5 to 2.0 dB. Furthermore, the AlGaN LNA will have a larger dynamic range, an important attribute for many multi-signal systems.

Several open issues and challenges for AlGaN HEMTs were reviewed. These include developing an improved understanding of their device physics as well as improving material quality, including the quality and size of the semi-insulating SiC substrates that the active regions of the HEMTs are fabricated upon. Trapping must be further reduced in all device types. Device scaling must be addressed more systematically, taking into account material uniformity, thermal management, and gain compression. Finally, development of a useful WBG amplifier capability will require establishing full and robust MMIC processes for WBG materials, yield analyses, and assessment and assurance of a high level of device reliability.

The next section of Dr. Zolper's briefing described the status and potential of WBG microwave bipolar transistors. These devices, including both BJTs (bi-polar junction transistor) and HBTs, hold promise for providing improved linearity, power density, and phase noise, compared with FETs. Their overriding performance constraint is the limitation on their p-doping and on the associated minority carrier transport in GaN. So far, only DC results have been obtained for GaN-based BJTs and HBTs; current gains are typically less than 10. The primary research thrust in this area is to improve the p-doping efficiency and develop new device structures that mitigate the low p-type conductivity.

Next, a chronology of events leading to GaN MMIC development was described and compared to the history of GaAs MMIC development (see Figure 4). It was emphasized that development of GaN microwave technology has progressed more quickly than GaAs microwave technology did, partially as a result of the existing knowledge base available from GaAs development. With recent demonstrations of GaN MMICs, it was argued that the timing is correct for funding a WBG RF technology maturation program, equivalent in scope to the earlier DARPA GaAs Microwave and Millimeter Wave Monolithic Integrated Circuits (MIMIC) program, with the goal of bringing WBG RF technology to a level of maturity satisfactory for system insertion.

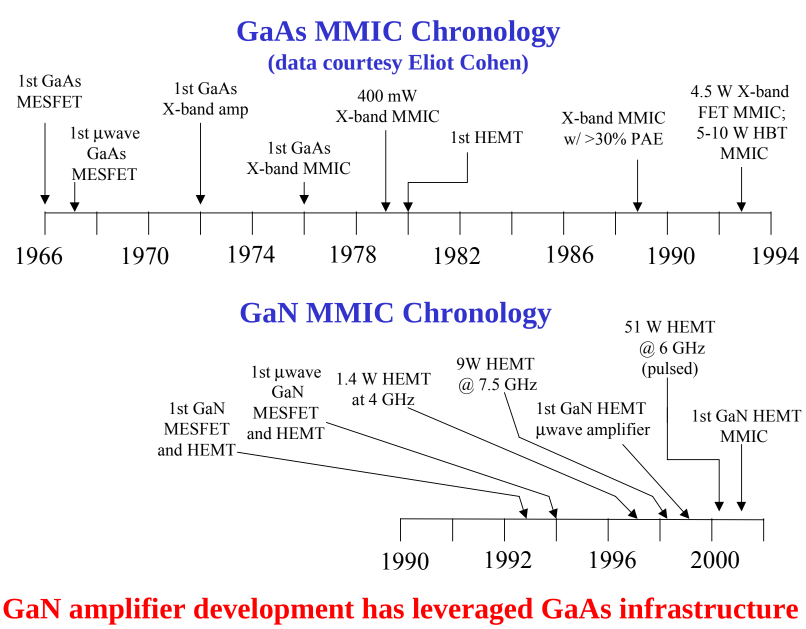

Figure 4: Chronology of GaAs and GaN MMIC development. The GaAs MMIC program at DARPA started at OSD in 1985 and was transferred to DARPA in 1988.

Joe Lawrence, DoN S&T Platform Protection FNC

This briefing presented the new Navy initiative called “Future Naval Capabilities” or “FNCs”. It was given by Dr. Joe Lawrence, Director of NRL’s Surface EW Systems (5740). There are 12 FNC topics. The "Platform Protection" topic was briefed in detail because it is most closely related to applications that would benefit from the use of wide bandgap RF technology.

The FNC process has been established to enhance transitions between the S&T and acquisition community. Each FNC has a representative for requirements, acquisition, resources, and an Office of Naval Research (ONR) executive manager. For the Platform Protection FNC, the representatives are: Requirements: RADM Paul Schultz, N86B Surface Warfare Directorate; acquisition: RADM Mike Mathis, SEA-05; Resources: Mr Dan Goldstein, N911; and ONR executive manager: Dr John Montgomery, Superintendent of NRL's Tactical Electronics Warfare Division (5700). The FNC process is designed to secure the "buy-in" of the acquisition community for ongoing and future S&T activities. Starting in FY02, 50% of 6.2 funds and 100% of 6.3 funds will be tied to FNC's and will have an acquisition sponsor.

During Dr. Lawrence's description of the FNC approach, examples were provided of the methods used to define future Naval requirements. For the platform protection FNC, five enabling capabilities were identified. These were, in prioritized order:

1. Ability to win or avoid engagements by torpedo mine weapons
2. Ability to win or avoid engagements by weapons/platforms, asymmetric threats, and non-lethal weapon threats encountered in the littorals
3. Ability to win or avoid engagements by airborne weapons and platforms encountered at sea
4. Ability to approach, enter, and operate in denied areas without being detected
5. Ability to resist and control damage from weapons while preserving operational capability

These enabling capabilities are achieved via use of "principal supporting technologies and demonstrations". There were four categories of these with associated sub-areas, as follows:

<u>MultiFunction/Multispectral Common Aperture Systems</u>
- **-MultiFunction/Multimode RF Systems**
- **-Multispectral/MultiFunction EO Systems**

<u>Multi-Dimensional Observability Management & Control</u>
- **-Above Water Signatures M&C**
- **-Below Water Signatures M&C**

<u>Configurations and Real-Time Re-Configurability for Damage Avoidance and Control</u>
- **- Damage Tolerant Structures**
- **- Advanced Electrical Systems**
- **- Automated Damage and Casualty Control**

<u>Short Range, Rapid Response,Littoral Engagement Defense</u>
- **-Undersea Weapons and Countermeasures**
- **-Ship Based Asymmetric Threat defense**
- **-Advanced Ship Self Defense Against Littoral Weapons**
- **-Subsurface Launched Anti-ASW A/C Weapons**

The most relevant area for application of WBG RF technology is Multifunction/Multimode RF Systems, (listed above under Multifunction/Multispectral Common Aperture Systems). The core demonstration in this area requires improved solid state power amplifiers, high performance ADCs, high speed DSPs, and digital beamforming. Both SiC and GaN based high power microwave amplifiers were specifically identified as enabling technologies for a large number of technology demonstrations and future transitions to platforms. Figure 5 is an example schematic showing the flow down from core demonstration, to identified technology, technology demonstration, and finally to transition-to-platform.

The requirement for SiC and GaN based microwave power amplifiers is predicated upon overcoming the limitations of the present end user terminal (EUT) in order to satisfy simultaneous needs for high power, wide bandwidth, and high linearity. Decoys have an additional requirement for small and cheap (throw away) transmitters. Finally, advanced electronic attack (EA) and electronic warfare (EW) systems have high duty cycle transmitter requirements that can presently not be met by use of crossed-field vacuum tube based amplifiers.

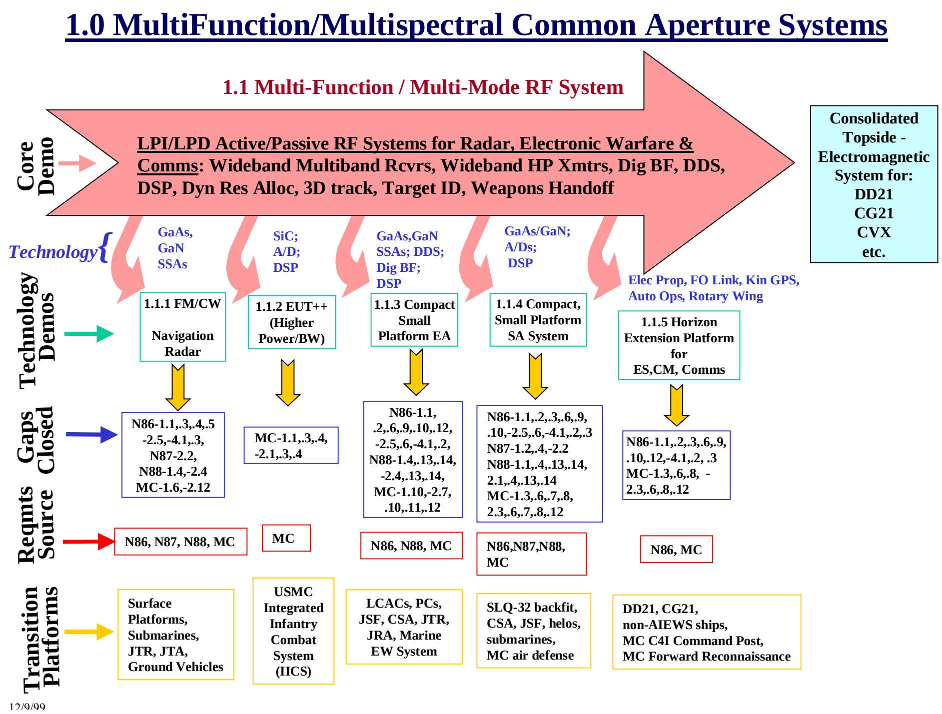

Figure 5: Schematic of Navy Platform Protection FNC flow down for Multifunction/Multispectral common aperture systems.

Max Yoder, Advanced Multifunction RF Concepts

Max Yoder, Director of ONR's Electronic Division, briefed advanced concepts for future electromagnetic systems. He addressed three main emerging technology areas: 1) 100 GHz digital logic, 2) wide bandgap solid state amplifiers, and 3) ultra dense, ultra fast, non-volatile, random access memories.

The ONR 100 GHz logic effort is based upon advanced scaling of InP-based heterojunction bipolar transistors (HBTs) via use of a low parasitic HBT design pioneered by Professor Mark Rodwell at UCSB. Dr. Rodwell's work has resulted in realization of the first transistor with a projected maximum frequency of oscillation (f_{max}) over 1 THz. Variations on the UCSB approach are being pursued by HRL and TRW to enable high-speed digital logic, eventually operating at a 100 GHz clock speed. This effort is expected to enable direct digital synthesizers for use in radar, EW, and communications systems. The TRW program has demonstrated a flip-flop circuit toggling at a record 84 GHz.

The wide bandgap effort follows from the ONR programs described by John Zolper. The primary advantages of wide bandgap semiconductors (SiC and GaN) were highlighted in relation to Si and GaAs. These advantages include:

- Higher Thermal Conductivity Leading to Greater Power
- Higher Dielectric Strength Leading to Greater Power
- Higher Dielectric Strength Leading to Higher Dynamic Range
- Ability to Move Electrons Faster Leading to Higher Frequency Operation
- Lower Dielectric Constant Leading to Greater Bandwidth

It is also expected that future electromagnetic systems enabled by transistors based on these materials will benefit from lower phase noise. This, in turn, will provide greater signal to noise ratios (SNR) than present systems have. The greater SNR will enable these future systems to operate much more effectively in the presence of clutter and jamming.

The status of SiC MESFET and AlGaN HEMTs was also described. It was noted that the system architectural goal for a large periphery AlGaN HEMT of >5 W/mm power density has now been demonstrated in a transistor with >50 W total power output.

The third technology area discussed was high-speed memory. These memories must be able to handle extremely large data demands for applications such as TBMD or network centric warfare. Memory technology developed at NRL and Carnegie Mellon University makes use of giant magnetic resistance materials, formed in a nanoscale "donut" shape, to produce a high-speed non-volatile core memory. An objective is to achieve a storage area density of 40 Gbits/cm^2 with ~0.1 ns access time.

The next portion of this brief addressed future system implications for the new technologies. The first of these is achievement of electronic beam steering through the use of direct digital synthesis. The second system implication is the possibility of realizing a fully digital transmitter based on pulse mode high power amplifiers fabricated with AlGaN technology. Achievement of these architectures would enable the beam formation to be software controlled. The flow down of these technologies into the platform protection FNC program, as briefed by Dr. Lawrence, was cast in a different way that illustrated their broad impact on future Navy systems.

The final portion of the brief was a review of system level trade-offs between conventional phase steered beams and true time delay steering as well as the tradeoff between pulsed systems and continuous wave systems. The bandwidth limitation of phased steered systems, due to the frequency dependence of their phase shifters, was noted and illustrated versus a true time delay system that is frequency invariant. True time delay enables handling large instantaneous bandwidth signals while the phase steered system will suffer from a large beam divergence.

TABLE II

FUTURE ACTIVE ARRAY RADAR CHALLENGES

Radar Function	Critical Transmit Module Characteristics
• Anti-Ship Missile Defense (Surface Search)	• High Power, Low-Phase Noise
• Air Defense & Air Traffic Control (Volume Search)	• High Power & Efficiency, Low Phase Noise
• Tactical Ballistic Missile Defense	• Very High Power, Broadband
• Target Discrimination	• Broadband
• Target Illumination	• High Power & Efficiency
• Navigation	• Low Power
• Low Probability of Intercept	• Low Power
• All Functions	• Very Wide Operating Bandwidth & High Linearity

The deleterious effect on system noise level resulting from the mixing of the carrier and modulation pulse streams was illustrated for a pulse mode system. The noise floor for the pulse mode of operation was noted to be over 50 dBc higher than for the comparable continuous wave system. The impact of the higher noise floor on Doppler radar detectivity was also noted. It was projected that the solid state CW system would have a noise floor up to 60 dB lower than that of present pulse mode vacuum tube systems. This would enable operation in high clutter environments, such as the littoral zone, as well as an increased radar detection range.

Finally, a concept was presented for CW mode radar based on the use of complementary orthogonal coding such as is accomplished using CDMA in wireless communications.

Greg Tavik, Midterm AMRF (Advanced Multifunction Radio Frequency) Testbed Demonstration

Mr. Tavik represented NRL's Radar Division effort on the Advanced Multifunction RF (AMRF) concept test bed. The NRL AMRF test bed represents the first step toward producing the direct digital beamforming system described by Max Yoder (see previous presentation) and is a clear system pull for wide bandgap high-power amplifiers. The present low-band test bed is expected to use SiC SIT amplifiers to cover the lowest portion of its operating frequency range, near 1 GHz.

Mr. Tavik next described the four AMRF test beds under development. They are: 1) a low-band transmitter, 2) a low-band receiver, 3) a high-band transmitter, and 4) a high-band receiver. The low band covers 1-5 GHz and the high band 4-20 GHz. The present test bed architecture uses sub-array allotment for separate functions. The use of wide bandgap amplifiers is expected to provide higher power, linearity, and efficiency compared with conventional solid state or vacuum tube amplifiers. A technology transition schedule for AMRF was presented. It is anticipated that insertion of wide bandgap amplifiers will take place in FY05. This insertion will be into AMRF-C version 2, which is intended to also use direct digital synthesis.

The remainder of Mr. Tavik's brief addressed future challenges for active array radar. The critical role of high power solid state amplifiers was emphasized. A summary of future active array challenges is given in Table II and current transmit module problems are itemized in Table III.

Transmitter module characteristics need improvements in four areas: 1) linearity for elimination of low harmonic and spurious transitions, 2) broad operational bandwidth, 3) broad instantaneous bandwidth, and 4) high efficiency. Mr. Tavik concluded by emphasizing that high power transmitter module performance is critical to enable future radar systems. This is the focus of wide bandgap microwave technology development.

Ben Shanabrook, Wide Bandgap Electronics Materials: Roadmaps and Epitaxy Issues

Dr. Ben Shanabrook, from NRL's Electronic Materials Department (6870), gave a tri-Service overview of WBG substrate and epitaxial growth developments. He first presented the challenges (shown in Table IV) for WBG electronic materials intended to be used for fabricating RF power devices.

Many of the key points raised by Dr. Shanabrook were also highlighted by other speakers during the STAR. These include recognition of the needs for: 1) ≥ 3 inch semi-insulating substrates[4], 2) continued reduction of substrate and epitaxial layer defect levels, and 3) continued improvement in GaN material quality (possibly including development of GaN substrates).

TABLE III
CURRENT TRANSMIT MODULE PROBLEMS

- Limited Power-Bandwidth Product
- Class-C Operation
    - Very-Low Dynamic Range
    - Only Saturated Waveforms Supported
    - Poor Linearity
- HPA Efficiency May Limit CW Transmit Power
- Large HPA Size
- Poor Linearity
    - Module Limited to Single Transmissions

[4] Because of the large size of the devices, larger substrates are needed in order to make device production economically feasible.

The Technical Panel for Electron Devices (TPED) roadmaps for SiC and GaN materials development were presented.[5] These roadmaps show ongoing efforts for core material developments as well as projected (presently unfunded) efforts. Each program is labeled with a maturity key as follows: R= R&D results; P= prototype demonstration, and A= affordability effort.

The largest SiC substrate efforts are Air Force programs, including in-house, DUAP and Title III funded work. The Title III effort was addressed in detail by Laura Rea in a subsequent brief[6]. However, it is important to recognize that none of the funded programs are specifically focused on fabrication of semi-insulating substrates. "Out-year" Air Force efforts are expected to shift focus from substrate development to WBG epitaxial development.

TABLE IV
Wide-Bandgap Electronic Materials Technology

Challenges

- RF power device production requires substrate diameter >3 in.
- High resistivity substrates required for planar RF device technology.
- Defect levels must be reduced to avoid compensation and to improve dielectric strength.
- Immature GaN materials technology base
  - No isostructural lattice-matched substrate available for GaN.
  - No reliable shallow p-type dopant exists for GaN.
  - High-background doping concentrations

SiC epitaxial growth status was also reviewed. Excellent growth morphology and low background impurity levels ($< 10^{14}$ cm^{-3}) have been achieved. Both n- and p-type doping can be well controlled to levels of 10^{15} cm^{-3}. Two commercial companies are now selling SiC CVD systems (Emcore and Aixtron). Three companies are presently acting as commercial epitaxy foundries (Cree, Sterling, and TechnoloGy and Devices International, Inc. [TDI])).

[5] These roadmaps are constantly updated to reflect ongoing and projected areas of DoD investments. They can be made available to DoD representatives or approved contractors. Distribution details can be obtained by contacting the Secretary of the Advisory Group on Electron Devices, c/o Palisades Institute for Research Services, Inc, 703-413-1282.
[6] See Laura Rea presentation summary, beginning on page 37.

Next, the status of GaN epitaxy was presented. N-type doping over the range from 10^{16} to 10^{20} cm^{-3} is possible; the p-doping range is limited to free hole concentrations of 10^{17} to 10^{18} cm^{-3}. While dramatic advances have been made, continued improvement is needed in controlling both doping type and background impurities level. A key issue is the lack of a bulk GaN substrate or other suitably lattice matched substrate. This deficiency results in device layers with high ($>10^{8}$ cm^{-2}) dislocation densities. The impact of these dislocations is device specific. An example was given of the presence of high reverse leakage current in GaN PIN diodes. This leakage can be at least partially attributed to the presence of a high dislocation density. In devices where current flow is perpendicular to dislocations (e. g., AlGaN HEMTs) the dislocations appear to have a less deleterious effect. Two commercial vendors of GaN MOCVD reactors were identified (Emcore and Aixtron), and three vendors of AlGaN MBE reactors were identified (Riber, VG, and EOI). AlGaN HEMT epitaxial material can be purchased from Litton-Airtron/Nitronix, ATMI/Epitronics, and Emcore.

Approaches for achieving suitable GaN substrates were reviewed. These include "fast epitaxy" processes such as HVPE and defect "filtering" techniques. The latter includes LEO and Pendeo-Epitaxy whereby threading dislocations are eliminated via various geometric masking and growth techniques. These techniques have been used to achieve GaN-based blue laser diodes with CW lifetimes over 10,000 hours. However, they have not yet been applied to production of large periphery microwave devices. True bulk boule growth of GaN, or AlN, and subsequent wafer slicing, remains an opportunity for basic research and technology development.

Laura Rea, Bulk Materials Issues

Ms. Rea is from the materials directorate at Air Force Research Laboratory. The Air Force has been the lead Service for several WBG bulk substrate programs. The focus of Ms. Rea's programs has been at the 6.2 (applied research) level and higher. That is, the work is primarily material technology transition from basic research to production. As such, Title III programs represent a significant portion of the overall effort and were described in detail.

The significant progress that has been made in improving SiC substrate quality over the past 5 years was described. In 1995, the problem of a high density of micropipes (open core screw dislocations) in SiC wafers was thought to be insurmountable; nearly all available substrates were 1 3/8-inch in diameter and two inch diameter SiC wafers were only at a demonstration stage. Semi-insulating SiC was not commercially available. Presently, micropipe densities in n-type SiC substrates have been reduced to < 30 cm^{2} in commercial products, 3-inch n-type 6H SiC substrates are commercially available, and 2-inch semi-insulating 4H SiC is also sold commercially. Four-inch 6H SiC substrates have now been demonstrated by Cree but are not yet a commercial product. The progress in growth of SI-SiC has lagged that for n-type substrates due to the larger market for the latter, primarily for power switching device applications and substrates for GaN LEDs.

A recent critical development has been the establishment of SiC wafer vendors other than Cree. This is important because a second source will be necessary for future acquisition programs. The other U.S. SiC vendors include Sterling Semiconductor which is selling SiC wafers (Sterling has announced it is being acquired by Uniroyal Technologies Inc. and plans to expand their SiC business), Litton-Airtron (which licensed the SiC bulk substrate technology developed at Northrop Grumman), and II-VI Inc. The emergence of these additional sources of supply are expected to accelerate the process of driving down substrate cost and increasing their availability for DoD programs.

Ben Shanabrook also discussed the status of bulk GaN substrates. It is not as encouraging as the status of SiC. Presently, there is no established technology base for growing GaN boules that are suitable for producing semiconductor quality wafers. Some "quasi-bulk" approaches are showing promise for realizing free standing GaN wafers. HVPE, also mentioned by Dr. Shanabrook, is the leading technology to produce quasi-bulk substrates. ATMI has demonstrated large, crack free, low defect density (dislocation density < 10^7 cm^{-2}) GaN substrates. Two Asian companies (Sumitomo and Samsung) also claim to have a process for producing GaN wafers based on HVPE growth. Availability of GaN substrates is expected to enable improved epitaxial device layers; however, the question of how severely the lower thermal conductivity of GaN compared to that of SiC will limit microwave device performance remains to be resolved.

Other potential bulk materials suitable as substrates for GaN epitaxial growth were discussed. AlN is an attractive choice because it has a slightly better lattice match to GaN as compared to a SiC substrate, a closer coefficient of thermal expansion, and good thermal conductivity (~3 W/cm K). Some success has been achieved with bulk growth of AlN--1-cm diameter boules have been reported.

ZnO has also been considered as a possible substrate for GaN growth since it has a similar lattice constant. A hydro-thermal process has been used at AFRL to achieve bulk ZnO crystals. To date, use of ZnO for GaN growth has been hindered by ZnO being incompatible with MOCVD growth, since it is etched by hydrogen. It may, however, serve as a useful substrate for MBE growth of III-Nitride material. However, the low thermal conductivity of ZnO and its present high background n-type conductivity will limit its applicability as a microwave device substrate.

Bulk materials needs were summarized as follows: 1) improved technical performance, 2) availability, and 3) affordability. To achieve improved technical performance, basic research is needed on SiC material properties, particularly concerning semi-insulating mechanisms, the causes and effect on devices of dislocations, and the cause and elimination of traps. Adequate availability of appropriate material for producing devices will be reflected by the achievement of three-inch diameter semi-insulating substrates (SiC and/or GaN) with suitable polish/surface finish. Multiple sources of this material are needed. While significant progress has been made toward increased material availability, continued support is needed, particularly to establish sufficient sources of supply for semi-insulating material. Finally, to achieve affordability, especially for semi-insulating SiC, work is needed to improve wafer yields and optimize processing and material uniformity.

The final portion of Ms. Rea's briefing addressed the Air Force Title III program. Its mission is "to create assured, affordable, and commercially viable production capabilities and capacities for items *essential for national defense*." This program has played an essential role in the maturation of Si, GaAs, InP, SOI, and now SiC substrate technology. The SiC Title III program efforts will be coordinated with other relevant service activities.

The manufacturing objectives of the on-going Title III program for SiC substrates are shown in Table V. Due to the commercial orientation of the program, there is no specific emphasis on producing semi-insulating SiC substrates. Instead, the program is directed toward increased wafer diameter (primarily of n-type wafers), continued reduction of micropipe density, improved processing yield, and reduced process cycle time. There is also a task aimed at realizing 4-inch diameter wafers.

Three contracts have been awarded, with total costs being shared on a 50/50 basis between government and industry. The awards are to Cree Inc ($4M total, $2M government funding), Litton-Airtron ($7M total, $3.5M government funding) and Sterling Semiconductor ($6M, $3M government funding). The program has tri-Service oversight. It includes characterization of the resulting SiC substrates.

Table V

Title III Silicon Carbide Substrates Project Objectives: Manufacturing

- Establish manufacturing processes (crystal growth, slicing, polishing) for consistent, high quality, large diameter (~75mm), electronic grade SiC substrates
- Demonstrate a 75KSI/YR production capability for 75mm, electronic grade SiC substrates
- Implement manufacturing process improvement using statistical process control, design of experiments and benchmarking techniques in order to:

  -Improve production process yields >50% - Increase boule size

  -Reduce micropipe concentrations to <5/cm2 - Reduce impurities

  -Reduce process cycle time - Improve flatness

  -Improve substrate surface characteristics - Reduce cost >50%
- Establish a quality assurance system certified to ISO 9000 quality standards
- Demonstrate feasibility of manufacturing 100mm, electronic grade SiC substrates

The briefing concluded with the reiteration that: 1) semi-insulating SiC is not yet sufficiently affordable or available; 2) bulk GaN is still an area needing additional basic research support, although results of on-going work are starting to show promise; and 3) other materials, primarily AlN, may have a role to play as substrates for GaN-based device epitaxy.

Thomas Jenkins, Wide Bandgap Technology for RF Applications

Tom Jenkins, from AFRL/SNDD, presented the Air Force perspective of WBG RF applications and technology development. He began by showing many potential opportunities for WBG RF technology to play a role in improvement of Air Force systems. These include the "more electric" aircraft, UAVs, UCAVs, space systems, radars, decoys, seekers, and jammers. He described the regions of power versus frequency space (as shown in Figure 6) where SiC and GaN

RF technology is expected to be valuable. The frequency break between the applicability of the two materials was shown to be near 10 GHz.

Mr. Jenkins discussed a road map for solid state RF power. This roadmap encompassed all of the solid state RF power technologies, not just ones based upon wide bandgap semiconductors. It addressed the joint warfighter capability objectives of information superiority and precision force. The principal technical challenge was identified to be “more capable solid state RF power amplifiers”. Development plans for wide bandgap RF must be in the context of these roadmaps to ensure wise investment of DoD’s limited budget.

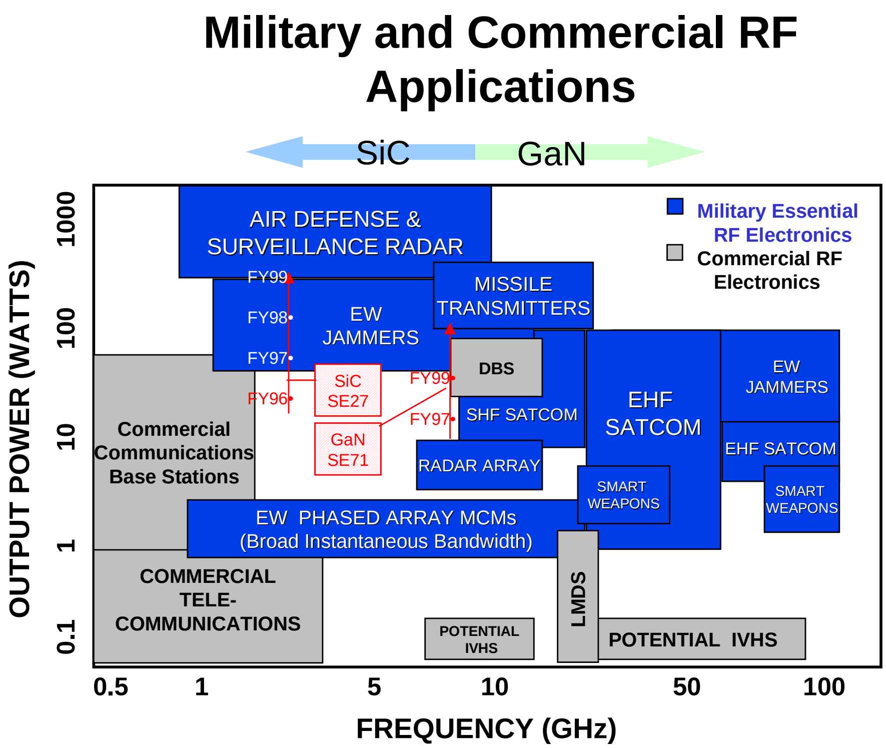

Figure 6: Military and commercial applications as a function of output power and frequency range requirements

SiC and GaN based amplifiers are cited in this road map as promising candidates for addressing high power applications at frequencies ≤ 20 GHz. SiC and GaN based amplifiers are cited in this road map as promising candidates for addressing high power applications at frequencies into the Ka-band, in the near-term. FY01 funding of $4.4M is shown. Unfunded programs listed total $8.5M.

In response to Mr. Yoder’s assertion concerning Navy MDAPs (Major Defense Acquisition Program), Jenkins stated that the Air Force has not been successful in persuading MDAP offices to identify wide bandgap RF technologies as being critical to their mission success. Mr. Yoder noted that it took three years of high level briefings to Navy management to gain support for advanced solid state technology development. Wide bandgap RF is a principal component of this technology area. The MDAP offices need to be convinced of the additional capabilities that this new technology will provide for their platforms.

AF investment strategy for WBG RF technology development was described as attempting to leverage from commercial and photonics investments while exploring the new "concept of operation (con-ops)" and system level trade-offs that WBG RF technology will allow. The implications of robust GaN-based RF technology for system level use were described as the ability to: 1) reduce aperture size by 1.8x, 2) improve range by 80%, 3) improve efficiency through 3x reduction of prime power and elimination of lossy combiners, 4) reduce mass and volume by 2x, and 5) reduce cost.

The Air Force's in house and contract research on WBG materials and devices was discussed next. Basic research on material defects has been conducted as well as work on bulk crystal growth. Device related work includes a DUST contract to Cree to develop high-power, high-temperature, radiation-tolerant GaN microwave devices, a contract with Northrop Grumman to develop S-band SiC SITs, a BMDO funded GaN amplifier program with TRW, a BMDO funded high power amplifier packaging effort with Raytheon, and several SBIR contracts. The Air Force funding in FY01 for development of robust WBG devices and circuits was $824K.

Mr. Jenkins' briefing concluded with a description of perceived insertion issues for WBG RF technology. These include the need for: 1) an assessment of how much RF technology can leverage from the commercial WBG photonics-related market, 2) understanding the role of substrate and material defects, 3) addressing affordability, 4) addressing availability via foundries, materials vendors, etc., and 5) obtaining reliability data (very little, if any, data exist to-date).

James M. McGarrity, U. S. Army Programs

Dr. McGarrity described the Army's Future Combat System as being lightweight, multi-mission capable, overwhelmingly lethal, yet strategically deployable, self-sustaining and survivable. A list of potential system applications for WBG technology was given. They spanned the frequency range from S-band through W-band. The potential impact of WBG technology is higher power, efficiency, and/or dynamic range. Performance requirements were summarized by function -- i.e., requirements for transmitters included: a compact footprint, higher power and efficiency; for receivers, requirements were: lower noise, higher power handling capability, and higher dynamic range; for control devices: higher power and faster switching; and for power conditioning devices: higher power switching and higher temperature capability.

There is no on-going major effort for WBG RF development in the Army. However, related work on WBG high power switches (SiC) and UV detectors (GaN) is being conducted. The Army is leveraging investments being made by the other services, under Reliance. The Army Research Laboratory is interested in participating in WBG device and circuit characterization, device modeling, and material characterization. The Army focus is upon applications at frequencies above 30 GHz.

Bruce Kopp, Johns Hopkins University Applied Physics Laboratory

Mr. Kopp's brief cited the need for wide bandgap RF technology for total air defense. Mr. Kopp works closely with the BMDO and with Navy missile defense and radar programs. He was requested by the BMDO Advanced Radar Technology PMO to give the brief on their behalf. He began by describing the situational awareness needs of AAW (Anti-Air Warfare) and TBMD (Theater Ballistic Missile Defense) to achieve total air defense. This objective established a requirement for both S-band (for volume search radar) as well as X-band (for discrimination and tracking) radar.

Mr. Kopp stated that all future Navy radars are expected to be AESA -- where beam steering is accomplished by applying appropriate phase shift at each element. A major reason for the use of a distributed transmitter is achievement of reduced phase noise compared with a single amplifier architecture. Phase noise for a distributed system decreases by 1/sqrt(number of elements), corresponding to a 36 dB decrease in phase noise for a 4000 element array. Reduction in system phase noise translates to improved performance in the presence of clutter. It also enables operation in a high clutter environment or in the presence of jamming signals. An AESA also provides superior beam agility needed for high raid rates and increased overall system reliability, compared to a mechanically steered array.

A comparison was given of the number of elements and projected cost of a notional X-band radar that will be based on solid state power amplifiers. The comparison was between an array based on use of WBG (SiC or GaN) modules versus use of GaAs modules. A notional WBG array would require 16,750 elements (in a 7.5 foot diameter configuration) while the GaAs array would require 33,000 elements (in an 11 foot diameter configuration). The element count is per face with each radar having four faces. Based on an estimated ~25% yield of GaAs amplifiers and an estimated cost of $500/module, the cost of the GaAs based radar was deemed to be prohibitive.[7]

The discussion of achieving an acceptable WBG amplifier cost identified the need for high quality three-inch (and preferably four-inch) semi-insulating SiC substrates and a full MMIC production technology. The latter is needed to eliminate hybrid packaging costs. The three-inch substrate cost goal of $50/amplifier assumed a 50% end-to-end yield. The yield number could be relaxed if four-inch wafers of sufficient quality were available. Larger substrates would make it much more likely that cost goals could be achieved. It will also be necessary to achieve processing costs similar to those achieved at a fully loaded GaAs foundry.

Table VI summarizes the power amplifier needs of BMDO programs. It was noted that while power requirements can be met by combining Si (S-band) or GaAs (X-band) parts, cost and efficiency goals cannot be met with this approach; hence, the need for WBG amplifiers. SiC technology is being considered for S-band radars while SiC or GaN based devices may meet X-band requirements.

[7] In this example, a $1,000 SiC module would be needed to reach the same cost levels as a GaAs module.

Table VI: BMDO Power Amplifier Needs

	S-band	X-band
Peak Power (W)	> 200	> 25
Duty (%)	25	25
Amplifier Efficiency (%)	> 45	> 45
MTTF	> 40 Years	> 40 Years
Performance Maturity	2003	2003
Cost / Amplifier	< $200	< $50

The lack of any significant reliability data for SiC and GaN microwave amplifiers was noted. This data must be acquired as soon as possible to avoid developing a technology that may be inherently unreliable. The need to examine both thermal and voltage induced failures was noted since distinct physical mechanisms can be involved in separate and different failure mechanisms.

The final portion of Mr. Kopp's brief examined the critical role that thermal management plays in power amplifier operation. A model was presented comparing transistors built on GaN substrates to those built on SiC substrates. With GaN thermal conductivity of 1.3 W/cm K and SiC thermal conductivity of 3.3 W/cm K, devices built on the GaN substrate had a 80 to 186 °C higher junction temperature, depending on gate pitch and length. For GaN grown on SiC the junction temperature was much lower; this material combination appears to yield acceptable thermal performance.

In summary, Mr. Kopp reiterated that cost, not performance, limits future radar feasibility. It is the potential combination of low cost and high power of WBG amplifiers that will enable the S- and X-band radars needed by BMDO and the Navy. Further work must be directed, however, toward improving the size (three inch diameter is the minimum) and quality of semi-insulating SiC substrates and developing high yield WBG MMIC technology.

SUMMARY OF INDUSTRY BRIEFINGS

Technology

John Palmour, Cree Research, Inc., Durham, NC

Dr. Palmour presented two briefings. The first was a review of Cree's business perspective and the second an overview of SiC and GaN technology. Cree was clearly identified as an optoelectronics company that is directing its IR&D funds toward the development of commercial microwave components. With internal funding, Cree is developing SiC microwave components, primarily for operation in the 2-6 GHz frequency range and aimed at meeting needs of RF wireless applications. This company does not see a large commercial pull for GaN microwave devices, and it forecasts no commercial pull for pulsed-power MMICs. Cree acknowledged that it was acquiring Nitres. It plans to maintain current microwave efforts at both Cree and Nitres facilities and envisages an acceleration of GaN development, as a result. A significant conclusion from the business review is that, while Cree is committed to the commercial market, if it does not receive DoD funding the best that can be expected is a slow paced development of low-power CW discrete components that may be of little benefit to the DoD.

Cree's technology overview addressed the need for semi-insulating SiC wafers, the state-of-the-art of SiC MESFETs and GaN HEMTs, and trapping issues. Some significant issues, yet to be resolved, were identified. Semi-insulating SiC substrates are needed for their high thermal conductivity. High power devices are primarily thermally limited. These substrates also will provide the necessary electrical isolation and allow MMIC fabrication while reducing the complexity of thermal management. Substrate cost, which is dominated by wafer yield per boule, must be reduced. SiC-MESFET power density has been improving since 1996. In 1999, 5.6 W/mm was achieved at 3 GHz. A small periphery device yielded 36% PAE at 3.5 GHz[8]. A larger device yielded 80 W (CW) and 38% PAE at 3.1 GHz. In pulsed operation, Cree has demonstrated 120 W and 42% PAE at 3.1 GHz. A hybrid amplifier, using SiC MESFETs, obtained 30 W at X-Band. Preliminary life testing of SiC MESFETs indicated a failure activation energy of 2 eV and an extrapolated MTTF of 5×10^8 hours at a junction temperature of 150° C. Wide bandwidth SiC MESFET MMIC power amplifiers have been produced. Also, 25-W has been achieved over 2 octaves near S-band with a two-stage MMIC amplifier for the AMRFS program. Evidence of trapping was seen in the initial material. The substrates were improved to yield a 50% improvement in PAE, elimination of current drift, and reduction of output conductance. GaN/AlGaN HEMTs have been produced for 10 GHz operation that exhibit 52% PAE and 6.8 W/mm. A via hole process is used to enable MMIC amplifier development. A hybrid amplifier yielded 40.7 W (pulsed) at 10 GHz. A two-stage MMIC amplifier yielded 20 W peak power for one octave bandwidth.

The following developments are required to continue device and MMIC performance advances: programs to improve semi-insulating SiC substrates and to develop improved epitaxy, leading to decreased costs; GaN epi growth on larger area SiC wafers; understanding of trapping issues, packaging developments, additional reliability testing, and emergence of commercial applications requiring large numbers of devices leading to reduced costs for the DoD.

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[8] Subsequent devices fabricated in 2000 achieved 5.2 W/mm and greatly improved PAE of 63%.

Michael Adlerstein, Raytheon RF Components, Andover, MA

Dr. Adlerstein discussed technical issues related to WBG RF power devices, with emphasis on the advantages WBG materials could provide for increased power, efficiency and bandwidth. He also discussed the technical challenges that must be overcome in to achieve adequate thermal dissipation, improved material parameters, and higher performance device operation and yield. Raytheon has recently begun making a substantial internal investment with the goal of developing GaN HEMT technology for existing and future products. Raytheon's primary focus is on X-band devices for radar, and wide band power devices for ECM. Understanding and control of piezoelectric polarization charging is seen as a major issue, as well as control of surface charging. The latter is responsible for parasitic device gating and dispersion effects. The influence of (SiC) substrate material quality is seen as critically important. Important parameters include substrate conductivity, impurity levels and defect control.

The higher voltage operation of GaN HEMTs compared with GaAs HEMTs results in a load line with a 4X higher output impedance. This greatly simplifies the output match at a given power level. Raytheon estimates the power added efficiency of GaN HEMTs to be potentially better than that of GaAs HEMTs at a given power level due to easier matching, which eases circuit loss, higher transconductance, which minimizes drive power, and higher voltage operation, which minimizes the knee voltage effect. To realize such higher efficiency, it will be necessary to achieve appropriate harmonic response of devices and circuits. At least a partial MMIC process, including wafer thinning and incorporation of backside vias, is seen as necessary for high power for high power device operation. A further major consideration is thermal dissipation. Diamond heat sinks are likely to play an important role in achieving thermal management goals. Raytheon has demonstrated a thermal design using diamond, that was calculated to be capable of dissipating 50 Watts of average power while maintaining device junction temperature at below 200 degrees C with the baseplate at 75 degrees C. Finally, cost and yield improvements are seen as being primarily related to the realization and use of larger substrates (eventually 4" diameter). The possibility was raised of substrate recycling to reduce overall development costs. Baseline reliability studies are recommended as soon as practical.

Primit Parikh, Nitres, Inc. (now Cree Lighting Company), Goleta, CA

Dr. Parikh reviewed the requirements for gallium nitride power amplifiers for radar and communications. General motivation, such as high power density and high breakdown voltage, and expected benefits were discussed. Potential X-band applications cited were Theater High Altitude Area Defense (THAAD), airborne radar, and shipboard radar. Potential applications at K- through W-band were also identified. These include Longbow, operating at K- to Ka-band, MVDS (Multichannel Video Distribution System) digital radio at Ka- to Q-band, and BAT and missile seekers at V- to W-band. Technology demonstrations by Nitres were also discussed. For example, 9.8-W/mm of power density was obtained at 8 GHz, and greater than 60% PAE at 6.4 W/mm was demonstrated for a small periphery device. Nitres' integration approach is to use flip-chip technology on thermally conductive substrates, such as AlN, to achieve thermal management of high power circuits and devices. A 6-10 GHz amplifier was demonstrated that yielded 14 W (CW) at 8 GHz. A pulsed power result of 51 W was also achieved for an amplifier operating at 6 GHz.

Dr. Parikh listed the following key issues for successful product development: materials growth, device optimization, gain compression, reliability, reproducibility, thermal management, and cost. For example, a semi-insulating substrate at least 3 inches in diameter will be required to achieve reasonable costs, and further increases in substrate size would improve affordability. Improvements in device passivation, buffer layers, and metallization must be explored further. High gain compression, exhibited during saturated power device operation, overly degrades linearity and efficiency. Failure mechanisms need to be better understood to formulate methods for overcoming power and efficiency degradation under high bias stress. This will require exploration at both the device and materials levels. High reproducibility has not been demonstrated either wafer-to-wafer or within-wafer. Packaging developments to support high power density operation and for thermal management are required. Flip-chip technology is an innovative approach to obtain high performance, improved throughput and lower cost, particularly with the relatively immature material and device technology today. Preliminary estimates suggest that flip-chip IC technology can be very cost competitive to GaAs technology (which is about \$10 to \$20/W at X band) and possibly cheaper in the long run. The cost advantage for GaN devices is derived from the expected reduction in circuit size using GaN technology. Nitres anticipates that an investment of \$200M - \$1B over 3–5 years will be required to adequately mature the technology. This investment would leverage from previous Si and GaAs infrastructure and experience and from strategic partnering of the customers and manufacturers.

Doug Reep, Lockheed-Martin

Dr. Reep noted that Lockheed Martin (LM) is cultivating TriQuint (GaN) and Cree (SiC & GaN) as sources of wide bandgap (WBG) devices. Lockheed Martin has interest in WBG for radar, seekers, and electronic warfare applications. For seekers, it states that solid state offers advantages in radiated power, for these extremely small apertures. The advantage for system efficiency, based on the higher operating voltages allowed by WBG devices, is often overlooked even for large shipboard and ground based radar systems, where prime power is indeed limited. LM considers the high power output afforded by WBG devices a great advantage in cases where radar is aperture limited and possibly for millimeter-wave frequency applications where power is limited, if WBG devices prove capable at those frequencies. It also sees packaging advances - especially new approaches to thermal management - as essential for WBG exploitation. One approach it is examining is to substitute WBG devices for GaAs devices if cost allows. However, cost depends on yield; yield depends on process control; and process control requires a large investment in processing wafers. The commercial requirements for microwave devices are not large enough to generate the need for the required investment. Significant government investment is required to advance this technology for microwave applications.

William Stanchina, HRL, Malibu, CA

Dr. Stanchina presented results of HRL's GaN/AlGaN MODFET developments, and predicted future application of this technology to surface, air and space systems. HRL is concentrating on developing and producing not only X-band but higher frequency GaN devices. For a 0.15 μm MODFET, 4.0 W/mm CW power density at 20 GHz has been demonstrated. This HFETs minimum noise figure was only 0.6 dB at 10 GHz with 13.5 dB associated gain. Thus, excellent potential for producing a robust LNA was demonstrated. Scaling the gate length down to 0.05 μm yielded the first GaN HFETs operating above 100 GHz with Fmax and Ft values of 140 and 110 GHz respectively. A 1.6 Watt HFET with 49% PAE was measured on a 200 μm device at AFRL (Jenkins/Kehias). Promising results were described of achieving 11% standard deviation in mobility, over 23 consecutive wafers grown at HRL, as well as a 3% peak current variation over a 2- inch diameter wafer. All AlGaN/GaN wafer growth at HRL is by RF plasma assisted molecular beam epitaxy. At the present time, GaN HEMT power density is 10x higher than GaAs PHEMT density (6 W/mm vs 0.6 W/mm). Finally, HRL presented results of a 20W GaN MIC power amplifier in which four 1mm HFETs were used to produce 22.9W of CW power at 9GHz with 37% power added efficiency.

The HRL development roadmap includes development of the technology for a 20W GaN MMIC in 2001. A 50 Watt X-band MMIC demonstration is planned for 2002, including device demonstrations at Ka and Q-band (26-50 GHz.) Major challenges are: SiC substrate size, availability, cost, GaN substrate development, high quality epi development, control and elimination of traps, achieving device gate recess, passivation, robust ohmic contacts, modeling, thermal dissipation and MMIC process development. Applications are expected at frequencies up to the 60 GHz range during the next 7-10 years.

R. Chris Clarke, Northrop-Grumman

Dr. Clarke presented the cost (at the module level) and performance (bandwidth, efficiency, etc.) advantages of WBG devices for radar, EW, space-based, and commercial RF applications. Other advantageous properties include ability to operate at high temperatures, better thermal conductivity, higher operating voltage, etc. These characteristics help to also meet the requirements of applications other than RF ones. Northrop-Grumman has transferred and licensed its SiC crystal growth and wafer preparation (sawing and polishing) technology to Litton Airtron. Airtron also has a Title III award to achieve SiC substrate affordability. Northrop-Grumman has a unique multi-wafer SiC VPE epitaxy system but needs increased epitaxy capacity for use with larger diameter wafers. Northrop-Grumman has SiC devices in "pilot production" which have achieved impressive UHF, L-band, and S-band SiC SIT results -- long pulse devices have achieved up to 1100W at UHF with 80% efficiency, 900W at L-band, and 300 W at 3 GHz. At S-band, where uniformity is more critical, yields are low and manufacturing technology (MANTECH)-type programs are needed to optimize processes and enhance automation. These high voltage, high temperature devices present unique problems for packaging. Voltage arcing and reliability both need to be investigated. Northrop-Grumman does have DC yield statistics. An example of 66% DC yield was provided but 30% is more typical. Northrop-Grumman has demonstrated high power MESFETs - > 10W at X-band - and has separately demonstrated high efficiency (57%) and wide bandwidth (1-8 GHz) with a hybrid distributed amplifier.

Northrop-Grumman has also developed processes for MMICs such as long life capacitors and substrate vias. After pointing out the need for better substrates for GaN epitaxy, Clarke concluded that AlN is the key to defect free GaN films. It has structural and thermal advantages that other approaches do not offer. In conclusion, Northrop-Grumman recommends ManTech for SIT affordability, continued epitaxy development, WBG packaging development and development of bulk nitride (AlN) substrates for GaN.

Applications

Al Morse, Northrop-Grumman

Mr. Morse presented background information about silicon device based systems (SPS-40, ASR) and Northrop Grumman's plans to transition to use of SiGe and SiC (AMRFS, upgraded E-2, Wedgetail) during coming years to lower system costs through reduced parts count. SiGe transistors are now in full production at Northrop Grumman (5,000+ parts) while large SiC parts (400+ made) are now entering their full-scale production phase. Northrop-Grumman states that this capability is necessary because their is no other source of devices to meet its planned systems requirements. SiC devices discussed included recessed gate SITs (which provide high peak power and power density), the implanted SIT (which is lower cost and more production worthy), and the MESFET for operation at frequencies as high as X-band. Examples of broadband operation and production history were also provided. Northrop-Grumman described its AMRFS module and demo subarray as providing a measure of power and cooling requirements. The E-2C MSSTIC demo program, requiring 54 modules at 10 kW each (800W level devices), has begun. A more advanced, lightweight version will also develop 540KW for the ADS-18 program. This version will be based on 1350W transistors. Comparative material costs and yield statistics were presented. SiC chip throughput is 3% that of Si and 13% that of GaAs. SiC wafers are not "SEMI grade" in polish or flatness and, therefore, present difficulties during lithographic portions of processing. The need for better packages (devices are presently thermally limited) was strongly emphasized as well as the need for advanced bonding schemes to prevent arcing at the preferred high operating voltages of SiC SITs. An additional need exists for better uniformity of S-band devices to allow symmetric circuit matching and reasonable scaling. Device reliability has not been established. Mr. Morse reiterated the need for SiC SIT ManTech programs, continued SiC wafer and epitaxy development, advanced packaging, and bulk nitride (AlN) development, to address WBG RF affordability, performance, and availability issues.

An additional Northrop-Grumman presentation by Mike Fitelson covered the use of wideband power amplifiers to facilitate shared aperture architectures. Some low-band and high-band examples were given. Examples of some amplifier designs are given, e.g., a distributed GaN amplifier using dual gate FETs was presented.

David Laighton, Raytheon RF Components, Andover, MA

Laighton presented applications of WBG technology, primarily to ground based surveillance and airborne fire control radars, and wideband ECM transmit array systems. Possible applications to THAAD/GBR (Ground-Based Radar) were explained. Chip size reduction, higher power and efficiency yield to spec, and higher peak power performance are all potential benefits. Replacement of TWT amplifiers in ECM arrays with WBG devices could enable reduction of weight, power, cost and system complexity. The predicted potential of WBG is 10 to 50X higher power-bandwidth than GaAs at frequencies up to 40GHz. Military systems dominate in this frequency/power range, but DoD investment will be required to satisfy their needs. Mr. Laighton listed 19 DoD systems in X/Ku band that are potential insertion candidates for WBG technology because of their power and efficiency needs. Mr. Laighton described the predicted evolution of active element phased arrays from present individual “brick” style arrays, through multi-element packaging, eventually to “module-less” subarrays. To realize an eventual cost goal of under $100/element will require availability of advanced packaging as well as high yield MMIC technology. Raytheon's highly aggressive roadmap calls for $50-100 per element module-less subarrays using GaN HEMT power amplifiers to be demonstrated in 2002. Raytheon has already demonstrated a single-layer AESA .5 x .7- inch tile using two GaAs MMIC chips that produces 5W output. Upgrading to GaN could, theoretically, yield a 25W tile.

Major challenges for producing GaN HEMTs include: improved material quality/uniformity (both SiC substrate and GaN/AlGaN epi), improved thermal management/packaging, solution of device performance issues such as gate/drain lag, dispersion, and scaling to larger (3-4 inch) substrates. Raytheon’s goal is to demonstrate GaN power MMICs by 2003. They predict it will take at least 5 years to mature the technology sufficiently to meet DoD production requirements. Raytheon expects that much GaAs MMIC-related experience will be applicable. However, expanded heat sinking and high power testing capabilities will require additional development.

Raytheon summarized the predicted benefits of GaN versus GaAs as follows:
- 5x increase in chip power density
- 10x increase in chip power output at X-band
- 5-10 percentage points increase in efficiency at X-band
- increased system power efficiency
- up to 10x AESA performance increase at same cost, or 1/3 cost at same performance
- ½ the weight
- with attendant power supply and structure improvements, 10x performance at equivalent cost, weight

Earl Johnson, Lockheed-Martin

Mr. Johnson stated that Lockheed-Martin views WBG components as the key enabling technology for future UHF to X-band radars and seekers. Use of WBG technology is expected to provide improved range and discrimination, smaller size, and prime power and cooling advantages. Johnson cited airborne early warning, national missile defense, and battlefield surveillance as three examples of system areas that would benefit from use of WBG solid-state components. He also cited SPY-1F and G AEGIS transmitter production as ending in 2005. He prognosticated that future DD-21 and CG-21 systems would be prime opportunities for WBG insertion (SiC first, then GaN). First insertions might be as backfits, then baseline technology insertions would occur, beyond 2015. This projection applies, also, to Navy plans for theater wide defense. Cost projections are unclear, but seem high at $1700 - $2200 per channel for a T/R module in an array. Lockheed-Martin projects SiC device requirements out to 2010 at 70,000+ per year. It expects that a large investment will be required. Mr. Johnson concluded that WBG technology will not be affordable unless the technology is commercially driven.

PRINCIPAL FINDINGS

Materials:

1. The lack of a lattice matched substrate for GaN results in a high dislocation density (typically ≥ 10^8 cm^{-2}) in present AlGaN HEMTs. The presence of these dislocations appears to have little detrimental impact on the two dimensional electron gas (2DEG) mobility in HEMTs largely due to the large sheet electron density (>$1x10^{13}$ cm^{-2}) that screens the dislocations. The effect of dislocations on device reliability is unknown.

2. The size, quality, and availability of semi-insulating 4H SiC substrates are presently insufficient to support large DoD system programs. There is a DoD Title III program addressing SiC (both 4H and 6H) substrate size and quality; however, it does not directly address semi-insulating material (the focus is n-type wafers) which is required for microwave devices. At a minimum three-inch diameter (four-inch diameter is preferred) 4H SI-SiC is needed to meet T/R module cost goals for system insertion of WBG amplifiers. Presently, only two-inch SI-SiC wafers are commercially available, but only from one supplier in volume.

3. WBG epitaxy needs further improvement and fundamental understanding of background doping, large area uniformity, and reproducibility. As wafer diameter increases, development of larger area epitaxial growth processes must also be addressed.

Devices:

4. Wide bandgap (WBG) RF technology based on SiC and/or GaN offers a potential 10-fold increase in power at a given frequency over current GaAs technology. Small periphery GaN HEMTs have demonstrated a power density of 9.8 W/mm at X-band, seven times that of the best GaAs HEMTs. Large periphery (8 mm) AlGaN HEMTs have been demonstrated with 50 W (pulsed) of total output power at a power density of 6.5 W/mm, which is 10 times the power density in large periphery GaAs transistors.

5. The high operating voltage of WBG RF technology offers potential advantages in efficiency at the device level (PAE is equal to $(1\text{-}1/G)[(V_{br} - V_{knee})/(V_{br} + V_{knee})]$ where V_{br} is 10 times higher for WBG over conventional solid state), circuit level (more efficient combining as a result of higher transistor impedance), and subsystem level (the higher local bus voltage enables more efficient prime power distribution and conversion).

6. SiC microwave devices (MESFET and SITs) presently are more advanced in total power performance than AlGaN HEMTs. The SiC devices are projected to be limited in frequency of operation to near 10 GHz or below.

7. AlGaN HEMTs are projected to have superior efficiency over SiC MESFETs and InGaAs PHEMTs, at least through 30 GHz. The superior efficiency over SiC MESFETs has been demonstrated, but that over InGaAs PHEMTs is only a projection.

8. The large critical breakdown fields of SiC and GaN place the electrical limit of WBG transistors up to a factor of two higher than their thermal limit. To gain full device performance, thermal management is critical. High efficiency amplifiers (such as push-pull Class B) using WBG transistors may not be thermally limited which will enable higher efficiency operation (theoretical drain efficiency is 78.5 % for class B versus 50 % for class A).

9. Excellent proof of principle SiC and GaN microwave devices have been reported, but reproducibility and yield analysis have not been determined.

10. The large polarization effects in the AlGaN/GaN materials system enables a new class of device structures whereby the channel charge is induced without additional extrinsic doping. This results in a sheet electron density $>1x10^{13}$ cm^{-2} that is four times higher than a GaAs PHEMT.

11. Present GaN HEMTs have generally not incorporated recessed gates or pseudomorphic channels to improve performance as has been done in GaAs and InP technology. This may be an avenue for future device improvements.

12. GaN HEMTs have been demonstrated with 8-mm of gate periphery with a pulsed output power of 51 W at 6 GHz (representing a power density of 6.5 W/mm for the large periphery device), 12-mm of gate periphery with a pulsed output power of 40 W at 10 GHz, and 4-mm of total gate periphery in a hybrid amplifier with a cw output power of 20 W at X-band. A complete GaN MMIC with source vias has been demonstrated that delivered 20 W (pulsed) at 9 GHz.

13. SiC MESFETs with a gate periphery of 48-mm have yielded a cw output power of 80 W at 3.1 GHz and with a gate periphery of 12 mm has yielded a pulsed power of 30 W at 10 GHz.

14. Packaged SiC SITs have demonstrated pulsed power levels up to 900 W at L-band. They have not been readily scaled to S-band operation. The higher frequency operation is an ongoing area of research.

15. Microwave trapping effects are evident in WBG RF devices. These traps have been significantly reduced in the best devices, but this area requires more investigation.

16. Limited reliability data exists for SiC microwave devices and none exists for GaN transistors.

17. AlGaN/GaN HBTs are presently constrained by the low p-doping, low hole mobility, and low minority carrier lifetimes in the base. Only DC results have been reported.

18. Robust LNA's based on AlGaN HEMTs may relax the requirement on protection circuitry (limiter circuitry) in receivers. Robust AlGaN LNA's are expected to have superior dynamic range, bandwidth, and a lower overall noise figure compared to conventional LNA's with protection circuitry. For example, AlGaN HEMTs have demonstrated a noise figure (NF) of 0.6 dB at 10 GHz with 13 dB of gain and a breakdown voltage of > 60V. The best InGaAs pHEMT NF at 10 GHz is 0.3 dB, but with a breakdown voltage of only ~3V. The associated protection circuitry for the InGaAs pHEMT adds an additional noise figure of 0.5 to 2.0 dB, depending on the protection requirements.

19. WBG RF technology offers a significant (~10x) power-bandwidth product advantage over Si, GaAs, and InP technologies as a result of the high power density, high operating voltage, and high impedance.

Packaging:

20. Present packaging technology need to be improved to support the high power density and high operating voltage of some WBG microwave components. Packaging and thermal management may be the performance limiter for WBG microwave devices and amplifiers.

Markets:

21. There is a large commercial market for LED's and lasers based on GaN (>$400M in 1999 and projected to be $4.3 billion by 2009). In the near term, this material infrastructure can be leveraged for DoD WBG RF technology.

22. There is an emerging market for high purity SiC material for gemstones. DoD can leverage this market for SI-SiC substrate development since the high purity gemstone specifications are applicable to semi-insulation SiC substrates.

23. Initial commercial markets for WBG RF technology will be narrow band, low frequency (~ 1-6 GHz), and high linearity for wireless base stations. The commercial applications will not directly address DoD system needs. There is a limited commercial market for pulsed RF power.

24. Potential commercial markets for GaN HEMTs includes Local Multipoint Distribution Systems (LMDS), WLL, collision avoidance radar, and satellite links.

25. The first WBG RF component (a 10 W SiC MESFET at 2 GHz) has been released by Cree Inc. as a commercial product. The part has superior linearity compared to Si LDMOS, which enables less back-off, and thus, higher operating efficiency.

System Impact:

26. WBG RF technology is being considered for Navy Theater Wide (NTW) Ship Self Defense and Theater Ballistic Missile Defense (TBMD) radar's.

27. If the projected simultaneous high power, efficiency, and linearity of WBG microwave technology is realized, it should enable simultaneous multifunction electromagnetic systems.

28. WBG RF technology is projected to meet the power levels (40-100 W) presently obtained by microwave power modules (MPM) below 30 GHz.

29. WBG RF technology may allow low cost, versatile, energy-saving, decoys and UAVs.

30. AESAs are preferred to achieve low phase noise radar. WBG RF technology will enhance the performance of AESAs, especially when aperture size is limited, foremost by providing higher

power per element and secondarily by potentially achieving improved linearity compared to alternative technologies.

31. The higher operating voltage of WBG amplifiers will improve the efficiency of power distribution and conversion in some systems. For example, in an active electrically scanned array, the higher voltage DC/DC converter will have increased efficiency. In another example, some levels of DC/DC conversion may be eliminated in JSF where direct operation at 28 V is preferred.

32. Based on demonstrated transistor noise performance, AlGaN HEMTs may allow robust, high dynamic range, receivers with a simplified receiver design and a reduced overall receiver noise figure compared to present approaches.

PRINCIPAL RECOMMENDATIONS

The recommendations given below are in prioritized order, however, for WBG RF technology to be successfully developed the recommendations CAN NOT be funded independently in a serial fashion. The development must simultaneously encompass all the recommended areas since the material development can only be successful when it is intimately tied to RF device demonstrations. In practice, the program will be weighed towards material work in the early stages and move towards expanded device and amplifier work in the out years.

1. Substrate development for WBG RF technology should proceed in the follow prioritized fashion:

    i. Increased funding is required as soon as possible to establish multiple suppliers for four inch (three inch is an acceptable interim goal) semi-insulating 4H-SiC substrates that meet production specifications for microwave devices. The estimated level of new funding is $25-35M total over 4 to 5 years.

    ii. Basic research should be expanded on bulk and quasi-bulk semi-insulating GaN substrates, or alternative substrates that enable low defect GaN epitaxy and are amenable to the requirements for high power GaN-based RF device technology (e. g. high resistivity, high thermal conductivity, scalable to large diameter, and scalable to large volume production). As soon as available, these substrates should be incorporated into a prototype microwave device and material characterization effort. The estimated level of additional funding is $10 M over 5 years.

    iii. Thermal modeling must be done at the device and package level for any alternative substrate(s) prior to an advanced development effort beyond that recommended in item (ii) to ensure that the substrate does not impose a thermal limitation (over the SiC alternative) on the WBG RF device performance.

2. Increased funding is required for wide bandgap epitaxial growth as it relates to RF device production. This includes process development for moving to epitaxial growth on 4 inch (an interim goal is 3 inch) wafers. The estimated additional level of new funding is $50M over 4 to 5 years.

3. Increased funding is required for a comprehensive WBG RF device and circuit technology maturation program to take WBG RF technology to a level of maturity commensurate with EMD transition. A detailed technology roadmap must be developed to ensure transition opportunities are realized. A system impact study must be performed, or assembled from existing reports, to develop specific device and amplifier goals for the program consistent with insertion targets. The WBG RF technology program must be directly coupled to the substrate and epitaxy tasks noted in 1 and 2 above. The program must include quantitative device modeling, epitaxy, processing, testing, CAD, packaging, thermal management, failure analysis, reliability, cost models, statistical process control, and yield analysis. This DoD-wide effort should be programmed <u>no later than</u> POM FY03. The estimated level of new funding is $150-200M over 5 years.

4. A business plan should be developed to establish and maintain cost effective WBG RF technology for DoD systems. Areas should be identified that require specific DOD support. Maximum leverage should be made of alternative applications for WBG materials (e. g. opto-

electronics, gemstones, power switching, and commercial microwave) and conventional/commercial MMIC process technology.

APPENDICES

APPENDIX A

SPEAKER FINDING ATTRIBUTIONS

	SPEAKERS																								
Finding #	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
1					A	X	A		A				A												
2			X					A	A				C	B	A		A					X	**A**	A	
3			X		A	X	A		A				A	B	A				A			X			
4		X	X		A	X	A	A	A		A				A		**C**	**B**	A	A	X	X		A	
5		X	X		**B**				A						A		A	A	B	B		X		**B**	X
6		X	X					A	A						A			A		B		X			
7									A										B						
8		X	X		**B**	X	A		A		B							**B**							
9			X			X			A						A		A	?				X		A	
10		X	X		A	X	A		A				?		A			A	A		X	X			
11						X	A		A																
12			X						A										A		X				
13			X																						
14																						X	A		
15			X		A	X	A		A								A	A	A		X	X			
16			X			X			A						A		A	A	A	A	X				
17		X			A	X			A														A		
18									A						A			A		B	X				
19		X			A				A						A			**B**	A			X			X
20			X					A	A						A		A	A	A	B	X	X	A	A	
21			X	A				A	A				?	A	A				B						
22			X																						
23			X																						
24			X	A														**B**	B	B	X				
25			X																						
26										**B**							**C**			A			A	***X***	X
27									A		A														
28								A	A	A	A				A		A	A	A	A	X	X			
29									A	A					A					A					
30											A	**B**					A	A		A			A	B	X
31			X						A						A		A	A		B	X			A	X
32									A						A			A	A		X			B	
33									A		B						A	A				X		?	X
Finding #	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y

APPENDIX B

COMMENTS ON WIDE BANDGAP STAR FEEDBACK[9]

SPEAKER ID	NO.	LETTER	COMMENTS
A			
B	***Presented the following general comments:***		
	Materials are still a problem, particularly substrates for GaN, and high resistivity SiC.		
	Epi appears to be pretty well controlled and fairly elaborate structures can be grown		
	The effects of defects, dislocations, etc still need to be studied, but trends are positive and progress on reduction techniques is encouraging HFET's are the most promising electronic RF devices, but there are several problems that are not well understood, particularly (1) current slump, (2) premature saturation, (3) dispersion. There are hand waving arguments for the cause of these phenomena, but little hard data, and no solutions at present. The potential performance of the AlGaN/GaN HFET is an order of magnitude greater than for GaAs devices, and SiC FET's are 4-5 times better than the GaAs FET's.		
	Progress on device development is rapid, but recent work is on solidifying previous advances. That is, RF performance near ideal has been achieved in spot devices (particularly 4H-SiC MESFET's, and a couple of 'home-run' type AlGaN/GaN HFET devices). Effort is to increase the yield of good devices (SiC), etc., and to repeat the good results on the nitride FET's. p-type material and contacts in both SiC and GaN are lossy and limit device performance. It is not clear the p-type material can be effectively used in microwave/mm-wave devices		
	There is little evidence that HBT's in wide bandgap material will be successful. No good data has been reported.		
	Wide bandgap technology would profit from a MIMIC-type program. The technology is moving rapidly, but DoD budgets are small, with most money provided by the Navy. If the government doesn't provide the funds, it is doubtful that industry will support the technology. The technology for devices such as SiC FET's, AlGaN/GaN HFET's is rapidly moving towards insertions. A MMIC-type program would greatly aid this process.		
C			
D			
E	5	B	PAE is proportional to $(1-V_{knee}/V_{br})/(1+V_{knee}/V_{br})$, should be changed from $(1- V_{br} /V_{knee})$
	8	B	Suggested change: The large critical breakdown field of SiC and GaN place the electrical limit of the WBG transistors up to a factor of two higher than their thermal limit. To gain full device performance, thermal management is critical. High efficiency amplifiers (such as push-pull Class B) may not be thermally limited, however (the theoretical efficiency is 78.5% for Class B vs. 50% for Class A)
F			
G			
H			
I			

[9] The crossed-out text and other corrections and italics are part of the feedback received from the speakers.

J	26	B	The AMRFS program is addressing NTW and NMD functions with WBG devices as part of AMRFS Increment 2.
K	33	B	In addition, it provides the capability for self-gating and this is of significant importance to Electronic Warfare Systems.
L	30	B	Low phase noise radar also requires very high quality (low phase noise) oscillators and waveform generation. However, WBG RF technology, when used for the power amplifier in the transmit module, significantly reduces the residual phase noise contribution of the transmitter to the overall phase noise budget for the radar system.
M	2	C	2" semi-insulating SiC is available from Cree and Sterling. Title III program should push hard on semi-insulating materials.
N	2	B	*There is a* DoD *Title III program addressing SiC substrate size and quality; however, it does not* directly *address semi-insulating material which is required for microwave devices.* By improving purity, etc. for conducting substrates there is <u>indirect</u> benefit for the semi-insulating growth process.
	3	B	*Added at end: Development of large diameter epitaxial processes will be required as substrate diameter increases*
O			
P			
Q	4	C	L-band Si devices generate 300 watts, while S-band Si can generate 80 watts. I believe 3,000 watt and 800 w levels are unrealistic. If solid-state is modified to GaAs, the finding is fine.
	26	C	To my knowledge, the Navy has no official NMD role.
R	4	B	Useable power will depend on desired gain and efficiency.
	8	B	The large critical breakdown fields of SiC and GaN place the electrical limit of WBG transistors *above* ~~up to a factor of two higher than~~ their thermal limit. ~~This enables high efficiency class B push/pull circuits to be realized at full output power but with a commensurate higher efficiency~~. The theoretical efficiency is 78.5 % for class B versus 50 % for class A). To gain full device performance, thermal management *and high efficiency* is critical.
	19	B	WBG RF technology *should facilitate wide bandgap power MMICs* ~~offers a significant (~10x) power/bandwidth advantage~~ over Si, GaAs, and InP technologies as a result of the high power density, high operating voltage and high impedance
	24	B	*Potential* ~~Emerging~~ markets for GaN HEMTs includes LMDS, …
S	5	B	DE α (1- V_{br} /V_{knee}), PAE = DE (1-1/β). High Gain needed to get high PAE.
	7	B	Demonstrated over GaAs MESFETs, close to PHEMTS. However, efficiency with linear operation needs much work.
	21	B	LED & laser markets do not necessitate 4" SI substrates which are crucial for low cost electronics
	24	B	Emerging markets for GaN HEMTs includes Infrastructure (base stations) MMDS, VSAT… Markets such as LMDS are still 'concepts', not established markets.

T	5	B	Potential for improvements has not been achieved in devices/circuits so far.
	6	B	The Sic device are projected to be limited in frequency of operation to near 10 GHz or below as a results of f-limitation results from device parasitics ~~channel scaling restrictions~~.
	18	B	This is at present, an assertion that must be demonstrated. AlGaN-based LNAs may have relaxed protection circuitry requirements. No BW advantage is expected.
	20	B	'insufficient' may be too harsh, but packaging and thermal management are critical issues and must be addressed.
	24	B	No market knowledge
	31	B	Agree up to specific comment on JSF.
U			
V			
W	2	A	There is also a need for 3-inch n-doped 4H substrates for SITs. Only 6H is presently available in 3-inch.
X	5	B	In general I agree, but early results on WBG devices show pretty high knee voltages. High impedance load lines should be more efficient and broader bandwidth, but this is yet to be realized.
	26	N/A	'No Comment'
	32	B	Early results at Raytheon show some increased tolerance of LNA devices to power, but not enough to eliminate a separate limiter. Linearity is TBD.
Y			

APPENDIX C
GLOSSARY

AAW	Anti-Air Warfare
AESA	Active element, Electronically Scanned Array
AMRF	Advanced Multifunction Radio Frequency
APVT	Advanced Physical Vapor Transport
BJT	Bipolar-Junction Transistor
EMD	Engineering & Manufacturing Development
FET	Field-Effect Transistor
GBR	Ground-Based Radar
HBT	Heterojunction Bipolar Transistor
HEMT	High Electron Mobility Transistor
HFET	Heterostructure Field Effect Transistor
HVPE	Hybrid Vapor Phase Epitaxy
IMPATT	IMPact Avalanche Transit Time
LDMOS	Lateral Double-Diffused Metal-Oxide-Semiconductor
LEO	Lateral Epitaxial Overgrowth
LMDS	Local Multipoint Distribution Systems
LNA	Low Noise Amplifier
MAFET	Microwave and Analog Front End Technology
MBE	Molecular Beam Epitaxy
MDAP	Major Defense Acquisition Program
MESFET	MEtal Semiconductor Field Effect Transistor
MIMIC	Microwave and Millimeter Wave Monolithic Integrated Circuits program
MMDS	Multi-point Microwave Distribution System
MMIC	Monolithic Microwave Integrated Circuit
MOCVD	Metal Organic Chemical Vapor Deposition
MURI	Multidisciplinary-research University Research Initiative
MVDS	Multichannel Video Distribution System
PAE	Power-Added Efficiency
SIT	Static Induction Transistor
TAMD	Theater Air & Missile Defense
TBMD	Theater Ballistic Missile Defense
THAAD	Theater High Altitude Area Defense
UAV	Unmanned Aerospace Vehicle
UCAV	Uninhabited Combat Aerial Vehicle
WLL	Wireless Local Loop

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